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RADC-TR-73-334
Final Technical Report
November 1973

RELIABILITY ACQUISITION COST STUDY

General Electric Company

Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York

RELIABILITY ACQUISITION COST STUDY

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FOREWORD

This is the Final Report on Contract F30602-72-C-0226, Project 5519, Job Order Number 55190256, Reliability Acquisition Cost Study. It was prepared by the General Electric Company, Aerospace Electronic Systems Department, Utica, New York and covers the period May 1972 to May 1973. Technical surveillance was performed by Jerome Klion (RBRS), Rome Air Development Center, Griffiss Air Force Base, New York.

General Electric wishes to thank David F. Barber of RADC as well as Mr. Klion for their guidance and counseling throughout the study. Also, appreciation is extended to R. Bonner of the Naval Weapons Center and A. Hevesh formerly of AVCO Corporation for their time in discussing their work in previously performed studies of a similar nature.

This technical report has been reviewed and is approved.

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ABSTRACT

This report presents the results of a study to develop basic relationships capable of determining and predicting the acquisition costs attributable to equipment reliability. The study is based on data derived during the development phase of equipment acquisition. The relationships, including incremental reliability gain related to incremental reliability cost, were developed using data from two manufacturers on ten equipments covering three reliability elements. The equipments cover a span of end use airborne and space environments. The reliability elements analyzed in the study are the reliability design program (includes prediction, failure mode and effect analysis, and design reviews); the reliability parts program (includes parts screening specification, parts standardization and control, and vendor control); and the reliability testing program (includes evaluation testing, equipment environmental screening, and reliability demonstration testing).

To develop the relationships, two linear models were hypothesized. The first model relates resultant equipment reliability, the reliability costs and the equipment complexity. The second model relates incremental reliability element gain to reliability element cost.

Detailed discussions of data collection and analysis efforts along with step-by-step procedures for using the modeling results are presented in the report. Constraints and precautions to be applied in using the equational relationships are also included.

EVALUATION

1. The objectives of this study were to:

a. Develop relationships between resultant reliability and reliability development cost for avionic equipment.

b. Determine sensitivity relationships and trade-offs among the elements comprising a reliability program to resulting equipment reliability.

2. Both objectives were met. Sufficient valid data were available to provide the desired relationships with a high order of statistical significance. The data were such that two types of analyses were possible:

a. A macroscopic analysis which provided the various cost estimating, reliability estimating, and rudimentary trade-off relationships required.

b. A microscopic analysis which had as its objective the development of "Reliability Gain" relationships relative to various elements and subelements of a reliability program based on their cost and impact. The analysis had as its purpose the determination of the optimal allocation of resources to the various elements and subelements of a reliability program assuming "failure analysis and fix" feedback loops exist during the development/test program.

3. The results of the program will be used in trade-off and life cycle cost analyses providing a heretoforemissing link, a relationship between reliability development cost and resulting reliability. The results can also be used as a foundation to structure the optimum size and mix of a reliability program in a development environment similar to the one from which the data eminated.

4. This effort supports RADC Technology Plan TPO-13, Reliability, paragraph 3.13.2.2, Reliability Management.

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GLOSSARY

AEG	Active Element Group
AESD	Aerospace Electronic Systems Department of General Electric Company, Utica, New York
C_d	Reliability Design Cost*
C_d'	Reliability Design Cost Excluding FMEA*
C_{DR}	Reliability Design Review Cost*
C_{FM}	Reliability Failure Modes and Effects Analysis Cost*
C_p	Reliability Parts Cost*
C_{PR}	Reliability Prediction Cost*
C_{p+t}	Reliability Parts Plus Reliability Test Cost*
C_T	Total Reliability Program Cost*
C_{Ta}	Cost* Required to Achieve θ_a
C_{Tb}	Cost* Required to Achieve θ_b
C_t	Reliability Test Cost
e_i	Random Error
FMEA	Failure Modes and Effects Analysis
G_d	Gain in MTBF due to Reliability Design Program (θ_{out}/θ_{in})
G_p	Gain in MTBF due to Reliability Parts Program
G_T	Gain in MTBF due to Total Reliability Program
G_t	Gain in MTBF due to Reliability Test Program
K	Digital to Analog Cost Modifier

*Normalized and expressed in mandays.

LCL	Lower Confidence Level
MD	Mandays
MTBF	Mean Time between Failures
$M_{0.60}$	60 Percent Confidence Limit Multiplying Factor
$M_{0.75}$	75 Percent Confidence Limit Multiplying Factor
$M_{0.95}$	95 Percent Confidence Limit Multiplying Factor
N_D	Number of Component Part Drawings
N_{DA}, $N_{D(ANALOG)}$	Number of Component Part Drawings for Analog Equipments
N_{DD}, $N_{D(DIGITAL)}$	Number of Component Part Drawings for Digital Equipments
N_p	Number of Electrical Parts
N_{PK}	Number of Electrical Parts Normalized to Analog Configuration
R	Correlation Coefficient
$\underline{R}$	Reliability
R^2	Index of Determination
RET	Reliability Evaluation Test
RPM	Reliability Planning and Management
S_E	Standard Error of Estimate
S_Y	Standard Deviation
X_k	Other Prediction Parameters
α, β	Regression Parameters
θ	Mean Time Between Failures
θ_a	Desired MTBF within the state of the art

θ_b	Minimum MTBF within the state of the art
θ_d	Effective Achieved MTBF Resulting from Reliability Design Program
θ_i	Effective Achieved MTBF without Benefit of Reliability Program
θ_{imp}	MTBF Improvement
θ_p	Effective Achieved MTBF Resulting from Reliability Design Plus Reliability Parts Programs
θ_R	Resultant Equipment MTBF ($\theta_R = \theta_t$)
θ_t	Effective Achieved MTBF Resulting from Reliability Design Plus Reliability Parts Plus Reliability Test Programs

SECTION I

INTRODUCTION

1. BACKGROUND

The Air Force has indicated great interest in equipment reliability and equipment reliability costs. It has been apparent for many years that, for an additional cost increment during development aimed at making an equipment more reliable, many times that cost would be recoverable over the life of the equipment due to its improved reliability. While a number of studies have qualitatively addressed the cost/reliability problem or quantitatively addressed the cost-of-failure problem, only a few studies have attacked the problem of quantification of incremental development cost as a function of incremental reliability improvement. This study has used historical failure rate data along with historical cost data to truly quantify improvement in equipment reliability as a function of incremental reliability element cost.

2. STUDY OBJECTIVES

The objectives of this study were to develop relationships capable of determining and predicting the costs attributable to reliability during the development phase of electronic equipment acquisition. Further, basic relationships were to be developed equating reliability increments to increments in development cost. Specifically, the key objectives identified at the outset of the study were to:

- Develop a relationship between the equipment reliability and the total reliability development cost.
- Develop a relationship between reliability element costs and the equipment reliability.
- Develop relationships between reliability improvement and reliability cost for each of the reliability elements or groups of reliability elements.

3. RELIABILITY ELEMENTS

The study dealt with three reliability elements as they relate to ten equipments from two manufacturers. These elements are:

- Reliability Design Program - including prediction, failure mode and effects analysis (FMEA), and design reviews.
- Reliability Parts Program - including parts screening specification, parts standardization and control, and vendor control.
- Reliability Testing Program - including evaluation testing, equipment environmental screening, and reliability demonstration testing.

These elements and their composition are described in Section II.

4. DATA SOURCES

The equipments and their respective manufacturers were the magnetic tape transport from the Test Equipment Division of Honeywell, Inc., and four radar equipments, three digital equipments, a countermeasures equipment, and a military television equipment from the Aerospace Electronic Systems Department of the General Electric Company.

This study has also considered the results of two other studies done previously and independently. They were a cost analysis effort by the Naval Weapons Center, China Lake, California and the results of the work reported by Avco Corporation, Wilmington, Massachusetts (Ref. 1).

5. GENERAL APPROACH

The approach to the study was to hypothesize linear models (linear in coefficients but not necessarily linear in the variables) for developing relationships between equipment reliability and reliability cost; collect reliability cost data, reliability data (based on failure rate history) and normalization data on the various equipments; correlate the data; synthesize the data to the models and iterate the models to satisfaction. All of the data analyses were performed using time-sharing computer programs developed by the Information Services Business Department of the General Electric Company in cooperation with the General Electric Corporate Research and Development Center.

6. REPORT OVERVIEW

Section II describes the makeup of the reliability elements studied and details the efforts associated with collection and evaluation of the normalization, cost, and reliability data. Section III contains the analytical approach used in the study, while Section IV details the results obtained. Section V presents the conclusions and recommendations relating to this study and possible future efforts.

SECTION II

COLLECTION AND EVALUATION OF DATA

1. DESCRIPTION OF RELIABILITY ELEMENTS

This study investigated the three reliability elements (reliability design program, reliability parts program, and reliability test program) that are considered basic to the achievement of equipment reliability. Each of these elements is further broken down into three subelements or tasks. These elements and their component subelements are discussed below.

a. Reliability Design Program

The reliability design program consists of reliability prediction, failure mode and effects analyses, and design reviews. Each of these tasks is interrelated to every other task. For instance, the prediction is useful with the FMEA and both are used in design reviews. These tasks of the reliability design program are a prerequisite for the reliability parts program.

(1) Reliability Prediction

Reliability Prediction is used as a tool to ascertain the achievable MTBF for the design at various stages in the equipment development. The technique involves the use of stress ratios for each component part in the intended use environment to establish failure rates as described in MIL-HDBK-217A or the RADC Notebook. A prediction is derived for each assembly and inserted into a reliability model for the equipment to determine compatibility with the contractually required MTBF.

(2) Failure Modes and Effects Analyses

Failure Modes and Effects Analyses (FMEA's) are conducted during the design program to identify the effects of potential failure modes and potential system weaknesses on system performance. A functional flow diagram is developed to depict the series elements for the operational modes. Critical elements are identified for more detailed study, sometimes to the component level. Through these analyses, reliability improvement emphasis is directed to design areas critical to mission success.

(3) Design Review

Design reviews are conducted with Engineering and other related functions for assessment of the reliability design status and to identify and correct potential problems with the design. The results of reliability predictions and FMEA's are used as reliability tools during these reviews and to provide an early evaluation of alternative design proposals. Formal reviews are planned and held to a schedule based on the design status. Many informal reviews are also held between design personnel and a reliability engineer on an as-needed basis to assure the design will meet the contractual reliability requirement.

b. Reliability Parts Program

The second reliability element evaluated during the study was the reliability parts program, which consists of parts standardization and control, parts screening specification, and vendor control. AESD experience has shown that the reliability tasks making up the parts program yield parts with lower failure rates at lower cost. Therefore, it is considered essential that a comprehensive parts program be imposed as a prerequisite to the third element, the reliability test program.

(1) Parts Standardization

Parts standardization is essential to minimizing the number of part types used in an equipment. Through parts standardization, reliability efforts are directed to the control and screening of a minimum number of different part types in order to maximize the use of parts with known reliable performance. Additionally, control of parts for reliable application can be more rigidly maintained during the design phase. For example, a typical commercial equipment and a typical military equipment were compared. No parts standardization program was instituted for the commercial equipment; as a result, 70 percent more part types were required than for the military equipment of approximately the same parts complexity. Standardization like this offers three significant advantages: fewer part type drawings, fewer vendors, and lower part costs owing to price breaks on higher procurement quantities.

(2) Parts Screening Specification

While parts standardization efforts are directed to controlling part types in an equipment, parts screening efforts are directed at controlling the reliability of parts. These efforts include the investigation, preparation and negotiation of screening specifications to be applied to the component parts. These specifications include provision for operating

burn-in, monitoring of critical parameters during burn-in, in-line inspections, nondestructive environmental tests and providing data. The effectiveness of the parts screening specification effort has been assessed at AESD through analysis of test results on incoming parts. Nonscreened parts have been found to exhibit a defect rate approximately four times greater than for screened parts.[1]

(3) Vendor Control

Vendor control is the effort exerted to assure the attainment of reliable specialty items and subcontract hardware. This effort requires the same type of investigation, preparation and negotiation of specifications as parts screening but at a higher level of assembly. These vendors are monitored and controlled in the same way as component vendors.

c. Reliability Test Program

The third reliability element considered is the reliability test program. This element is comprised of three reliability tasks, namely, equipment screening, evaluation testing, and qualification/demonstration testing.

(1) Environmental Screening

Environmental screening at the equipment level, similar to the environmental test profiles specified in MIL-STD-781, is conducted to remove infant or early mortality failures from the equipment. The failures removed normally result from poor workmanship by component part suppliers and equipment manufacturers which is not detected during the normal factory in-process inspection and acceptance testing. The screening test also determines if the equipment is capable of meeting its performance parameters when subjected to the screening environment. The screening environment is generally compatible with the intended field use environments. Environmental screening tests are not intended to improve the reliability of the equipment in the same manner as reliability evaluation tests. For these reasons, the cost for planning and implementing environmental screening has been normalized to the average cost to screen one equipment.

[1] Although the cost to screen the part is not included in this task for purposes of this study, it is worth noting that AESD has experienced an increase of approximately one dollar per part on the average for screening in production.

(2) Evaluation Testing

Evaluation tests on initial equipments manufactured are conducted for extended periods to uncover design and manufacturing deficiencies that cannot be detected during the breadboard design phase. These tests are conducted at the equipment level to an environment of temperature cycling and periodic vibration patterned from MIL-STD-781. As test time is accumulated and equipment failures are experienced, each failure is carefully analyzed and cause of failure is determined. Corrective action is implemented where necessary and the effectiveness of the action is assessed during the continuing test. The costs of this effort exclude the material and labor to build the equipment(s) but include the test costs along with analyses and corrective actions.

Considerable evidence (see Appendix B) indicates that equipment reliability grows exponentially with accumulated test time during a properly conducted evaluation test.

(3) Demonstration Testing

During the reliability demonstration test phase, the equipment is exposed to a MIL-STD-781 environment to measure the MTBF achieved on the equipment as a result of the reliability elements imposed. Reliability demonstration impacts the reliability of the final product in two significant areas: (1) it provides an incentive to the equipment manufacturer to properly conduct the RDT&E Reliability Program since failure to meet the demonstration criteria usually carries severe monetary penalties to the producer, and (2) it provides for an assessment of effectiveness of corrective action prior to commencement of production. The costs of this effort exclude the material and labor to build the equipment(s) but include the test costs along with analyses and corrective actions.

For the purpose of this study, the MTBF measured at the end of reliability demonstration testing is considered to be the reliability achieved as a result of the RDT&E reliability elements imposed.

2. DATA COLLECTION

Following definitization of the reliability elements, the data collection effort was carried out. This effort was divided into three categories: (1) equipment characterization data, (2) reliability cost data, and (3) reliability data.

a. Equipment Characterization Data

The equipment characterization data is that data that could be used to assess distinct differences from one equipment to another. This data was reasonably easily defined and fairly straightforward to collect from historical files. The data is summarized in Table I.

b. Reliability Cost Data

The reliability cost data represents the effort expended during equipment development to perform the various reliability tasks. The costs were converted to mandays using the average AESD manpower labor rates applicable during the time span of development for each particular equipment. The time spans covered by the equipment in the study are shown in Figure 1.

(1) Normalization

It was realized at the outset that the equipments being considered covered a broad range of use environments, contract reliability requirements, types of designs (i.e., digital vs analog and new vs modified), number of development equipments, part complexities, degrees of part standardization and time era when developed. Consequently, it was recognized that it would be statistically desirable to perform some data normalization to reduce the number of independent variables and maximize the degrees of freedom in the analysis. Review of the data on the ten equipments led to a decision to normalize all equipments to an airborne, analog, new design configuration.

(a) Space to Airborne Normalization

A space environment is less severe than an airborne environment but the equipment goes through a more severe missile environment to reach space. Therefore, since this study only included one space equipment, it was assumed that on the average, the space equipment would be comparable to an airborne equipment with respect to use environment.

(b) Modified-Design-To-New-Design Normalization

Since the study includes only one equipment with a modified design, the historical data on that equipment was reviewed to determine the portion of the equipment (number and complexity of new circuits) that was

TABLE I. EQUIPMENT CHARACTERIZATION DATA BY EQUIPMENT

Normalization Variable	Equipment Letter Code									
	A	B	C	D	E	F	G	H	J	K
Resultant MTBF (hr)*	1350	225	188	225	141	501	46	237	133	209
Predicted MTBF (hr)	†	187	185	175	119	515	57	206	257	505
RDT&E Start	1/67	4/63	9/66	9/69	7/68	6/69	1/66	2/67	3/67	8/66
RDT&E Finish	8/69	9/67	2/68	5/70	9/72	1/72	11/67	10/69	4/69	3/67
Number of Electrical Parts	18,520	10,704	11,160	2,636‡	17,600	6,211	4,628	17,337	3,052	2,593
Number of Drawings	196	398	404	434	542	96	216	149	244	166

*60% LCL (Lower Confidence Level)
†Classified
‡Modified per paragraph II.2.b.(1)

modified. That is, on this particular radar, the quantity of parts that were new to the design was 2,632 out of the total quantity of parts of 11,545. Therefore, the quantity of parts for this equipment was changed to 2,632 to correspond to the portion of the design that was new.

(c) Digital to Analog Normalization

In general, a digital equipment of the same complexity as an analog equipment has fewer different types of parts and fewer different circuits. This means design and part costs will differ even though complexity is the same. It was decided early in the study to modify cost. In an effort to obtain a better assessment of this cost modifier, the relationship between number of electrical parts and number of part drawings was examined for the ten equipments. This relationship is shown in Figure 2. Since parts and design costs are directly related to complexity, a cost modifier was obtained by dividing the relationship for analog equipments by the relationship for digital equipments. It should be kept in mind that this relationship is based on historical data that resulted from part drawing standardization practices developed at AESD (Ref. 2). Anyone using these relationships should consult Reference 2 to assure consistency of practices.

The cost modifiers, as calculated from the Figure 2 relationships for the three digital equipments in this study, are summarized in Table II. These modifiers were applied to each respective digital equipment for the design discipline cost and the parts discipline cost only. The test discipline cost was left unchanged since it was assumed that the additional effort in design and parts would fully adjust off the digital to analog conversion. The reliability element cost data with modifiers applied is summarized in Table III.

c. Reliability Data

(1) General

In addition to the collection of the equipment characteristic data and cost data (which is used to develop the gross prediction equations), reliability data was developed on the basis of Engineering assessment of equipment failure rate history and used in conjunction with the equipment characterization data and cost data to develop the allocation equations. These allocation equations provide a quantification of the reliability contribution of each of the reliability elements. Both the gross prediction equations and the allocation equations are detailed in Section IV of this report.

TABLE II. DIGITAL-TO-ANALOG COST MODIFIERS

Equipment Type	Equipment Letter Code	Quantity of Parts (N_p)	$K = \frac{N_{D(ANALOG)}}{N_{D(DIGITAL)}}$
Programmer	A	18520	3.2
Processor	H	17337	3.0
Processor	F	6211	3.2

where

N_p = number of electrical parts

$N_{D(ANALOG)}$ = number of drawings for analog equipments

$N_{D(DIGITAL)}$ = number of drawings for digital equipments

K = cost modifier

TABLE III. RELIABILITY ELEMENT COST DATA (MANDAYS)

Reliability Element	Equipment Letter Code									
	A*	B	C	D	E	F*	G	H*	J	K
Design Program	6, 330*	1, 496	1, 087	658	893	1, 427*	713	2, 670*	675	707
Reliability Prediction	3, 165*	1, 036	761	452	487	649*	549	207*	527	544
Reliability Design Review	634*	460	326	205	203	131*	165	594*	148	163
Reliability FMEA	2, 531*	---	---	---	203	650*	---	---	---	---
Parts Program	12, 026*	4, 027	2, 174	986	2, 467	2, 467*	1, 098	5, 934*	1, 042	1, 142
Test Program	5, 094	4, 741	4, 458	1, 332	1, 989	1, 989	834	3, 343	815	946
Total $\bar{R}$ Program	23, 449*	10, 264	7, 719	2, 976	5, 883	5, 883*	2, 645	11, 947*	2, 532	2, 795

*Costs modified per paragraph II. 2. b(1).

The Engineering assessment of equipment failure rate history on Program E is included here as an example of how the incremental reliability data was developed. This equipment included the following reliability elements which are typical of the ten equipments in the data base.

- Reliability Design Program (periodic reliability estimates, FMEA and design reviews.
- Reliability Parts Program (develop and implement required parts screening specifications, parts drawing control, part drawing control, part selection, parts evaluation/qualification test and parts application criteria).
- Reliability Test Program (equipment environmental screening, reliability evaluation tests, reliability demonstration test).

The reliability program elements can be shown schematically as a series of events (Figure 3) with the feedback loops which are inherent in a well-integrated reliability program, such as that conducted on Program E.

The values of θ_i, θ_d, θ_p, θ_t and θ_R in Figure 3 were determined through a retrospect investigation of the reliability growth processes and effective achieved MTBF (θ) levels and milestones associated with each reliability program element. Upon establishment of the various θ's, and "inputs" and "outputs" of each element, the reliability gain (MTBF gain) for each element was calculated as

$$G_d = \frac{\theta_d}{\theta_i}; \quad G_p = \frac{\theta_p}{\theta_d}; \text{ etc.}$$

where

G_d = gain in MTBF due to reliability design program (θ_{out}/θ_{in})

G_p = gain in MTBF due to reliability parts program

G_t = gain in MTBF due to reliability test program

G_T = gain in MTBF due to total reliability program

θ_i = effective achieved MTBF without benefit of reliability program

θ_d = effective achieved MTBF resulting from reliability design program

θ_p = effective achieved MTBF resulting from reliability design and reliability parts programs

θ_t = effective achieved MTBF resulting from reliability design plus reliability parts plus reliability test programs

θ_R = resultant equipment MTBF ($\theta_R = \theta_t$)

(2) MTBF Contribution of a Reliability Test Program

The first pair of θ's established for the program was the input and output θ's for the test program. These values of θ, θ_p and θ_t (note, in this instance $\theta_t = \theta_R$, see Figure 3) were already obtained by comparing the well-documented reliability test results in the various phases of the reliability test program. Those costs associated with the corrective actions resulting from the test program that required reassessment of the design and parts program work elements are included in the overall test cost.

θ_t, the output MTBF of the test program, and the final or ultimate MTBF achieved through Program E's RDT&E reliability program is that MTBF measured in the Reliability Demonstration (Qualification) Test Phase of the reliability test program. For Program E, this MTBF was determined as:

$$\theta_t = \theta_R = 141 \text{ hours}$$

(3) MTBF Contribution of a Reliability Parts Program

Upon review of the test failures and test times associated with the environmental screening and reliability evaluation test (RET) phase of the test program, the input MTBF of the test program, θ_p (θ_p is the output of the parts program, see Figure 3) was determined. This was accomplished by using the test times of the equipment screening and RET phases and all failures accumulated in this time period. This effectively included inherent failures from isolated sources removed through equipment screening and failures of a pattern or correctable nature which were removed through the RET effort. For Program E, this MTBF was determined as:

$$\theta \text{ input to test} = \theta_p = 4 \text{ hours}$$

and the incremental gain due to the reliability test effort is:

$$G_t = \theta_t/\theta_p = \frac{141}{4} = 35$$

(4) MTBF Contribution of a Reliability Design Program

The next determination made was θ_p, the MTBF at the beginning of the parts program (the output of the design program). This determination was accomplished by evaluating the failure rate reduction achieved (MTBF improvement) through the parts program.

This effort involved a comparison of part failure rates. The part failure rates experienced in Program E were compared with the failure rates of similar items procured with no particular attention given to the achievement of high reliability.

A primary consideration of the analysis was a failure rate comparison of nonstandard parts procured to Program E imposed part disciplines to those which are procured to minimal military quality and functional standards. For instance, the impact on overall equipment reliability of imposing JAN-TX and ER level screening testing to small nonstandard electrical components and stringent environmental screening and qualification tests on specialty and major procurement items on Program E was assessed. The result of this assessment was that the MTBF improvement (θ_{imp}) achieved through the Program E parts program was about 2.5 hours. Therefore, θ_d, the output MTBF of reliability design program was determined from the expression:

$$\theta_p - \theta_{imp} = 4.0 - 2.5 = 1.5 \text{ hours}$$

(5) Initial Equipment MTBF

The initial reliability assessment of the Program E equipment showed that the proposed functional design would result in an average part failure rate of about 0.75 failure per 10^6 hours. This failure rate was unacceptably high in view of the contract MTBF requirement of the equipment. Through an integrated reliability design effort, which included FMEA, and audit of proposed design construction specifications, design adjustments were implemented and design application part stress levels criteria were appropriately reduced. Critical and/or potentially high failure rate items were identified and their impact on the equipment reliability, along with their maximum tolerable failure rates were identified to the parts program reliability engineers for their guidance and follow-up action.

A final reliability assessment was performed after the equipment design had been reconfigured to conform to the constraints developed by the reliability design effort. This assessment showed a predicted average part failure rate of about 0.50 failure per 10^6 hours. This reduction in average part failure rate (from 0.75 to 0.50 f/10^6 hours) results in an MTBF improvement (θ_{imp}) of 0.5 hour. From the relationship:

$$\theta_i = \theta_d - \theta_{imp}$$

and the value of θ_i is therefore:

$$\theta_i = 1.5 - 0.5 = 1.0 \text{ hour}$$

In summary, using the procedures described above, the incremental reliability (MTBF) of each reliability element and the quantized gain of each element for Program E are as follows:

$$\theta_i = 1.0 \text{ hour}$$

$$\theta_d = 1.5 \text{ hours}$$

$$\theta_p = 4.0 \text{ hours}$$

$$\theta_t = 141.0 \text{ hours}$$

$$G_d = \frac{\theta_d}{\theta_i} = 1.5$$

$$G_p = \frac{\theta_p}{\theta_d} = 2.7$$

$$G_t = \frac{\theta_t}{\theta_p} = 35.3$$

The incremental MTBF's and gains of the other programs were established in a similar manner. The results of these analyses for all 10 equipments are summarized in Table IV.

It should be noted that there is continuous feedback between the various major reliability elements (design, parts and test). For example, the results from a comprehensive reliability evaluation testing program provide significant data to allow for further improvement in the equipment design and the component parts utilized in the design.

TABLE IV. INCREMENTAL RELIABILITY MTBF AND GAIN DATA

Equipment Letter Code	Off-the Board MTBF θ_i	Initial + Design MTBF θ_d	Design + Parts MTBF θ_p	Design + Parts + Test MTBF * θ_t	Design Gain $G_d = \frac{\theta_d}{\theta_i}$	Parts Gain $G_p = \frac{\theta_p}{\theta_d}$	Test Gain $G_t = \frac{\theta_t}{\theta_p}$	Resultant Equipment MTBF * θ_R
A	7.0	20.0	95.0	1350.0	2.9	4.8	14.2	1350.0
B	2.0	3.0	11.0	225.0	1.5	3.7	20.5	225.0
C	3.0	5.0	16.0	188.0	1.7	3.2	11.8	188.0
D	5.0	8.0	26.0	225.0	1.6	3.3	8.7	225.0
E	1.0	1.5	4.0	141.0	1.5	2.7	35.3	141.0
F	11.0	15.0	67.0	501.0	1.4	4.5	7.5	501.0
G	5.0	8.0	20.0	46.0	1.6	2.5	2.3	46.0
H	2.0	5.0	15.0	287.0	2.5	3.0	19.1	287.0
J	3.5	7.0	25.0	133.0	2.0	3.6	5.3	133.0
K	15.0	22.0	60.0	209.0	1.5	2.7	3.5	209.0

*60% LCL

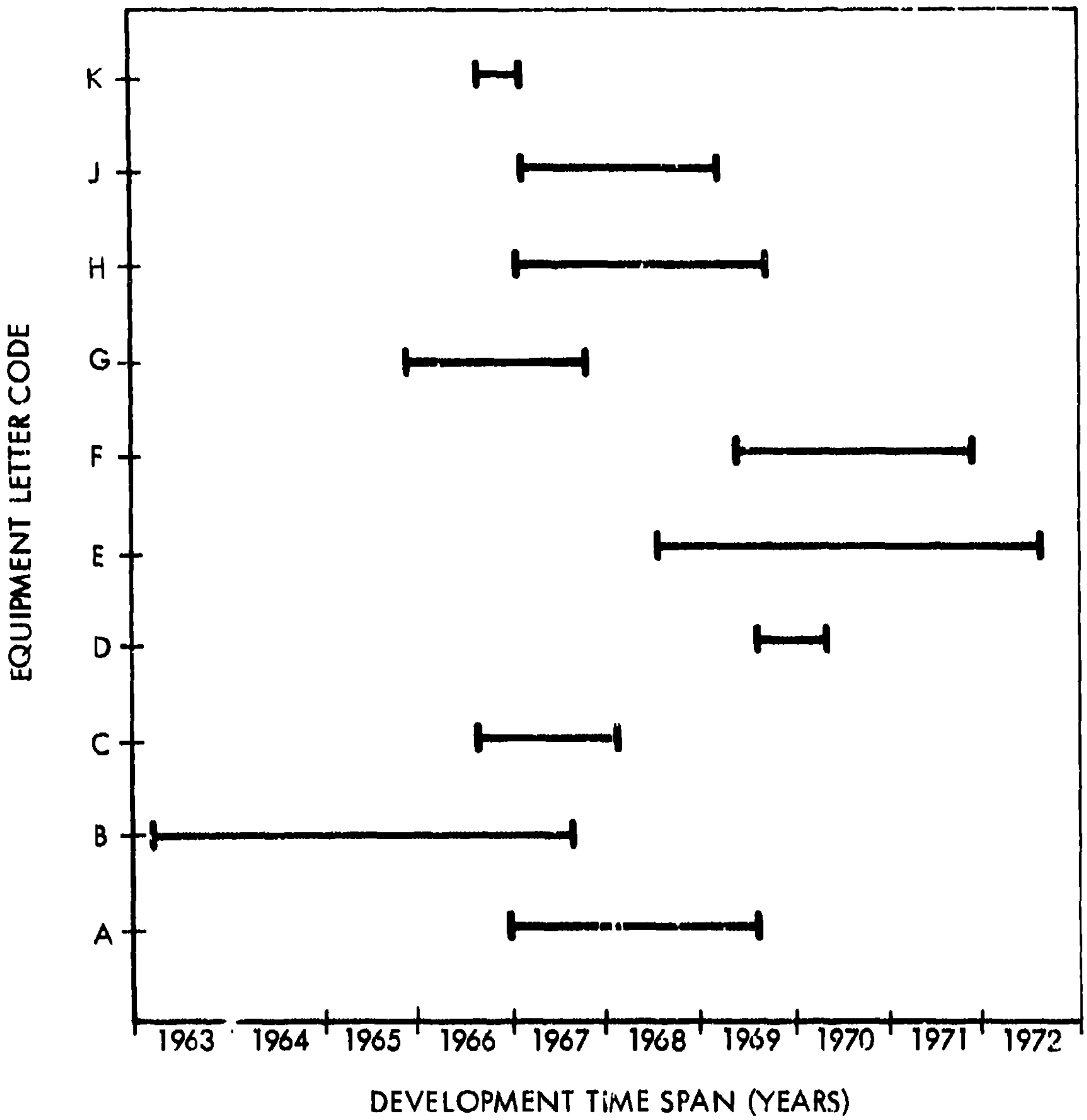
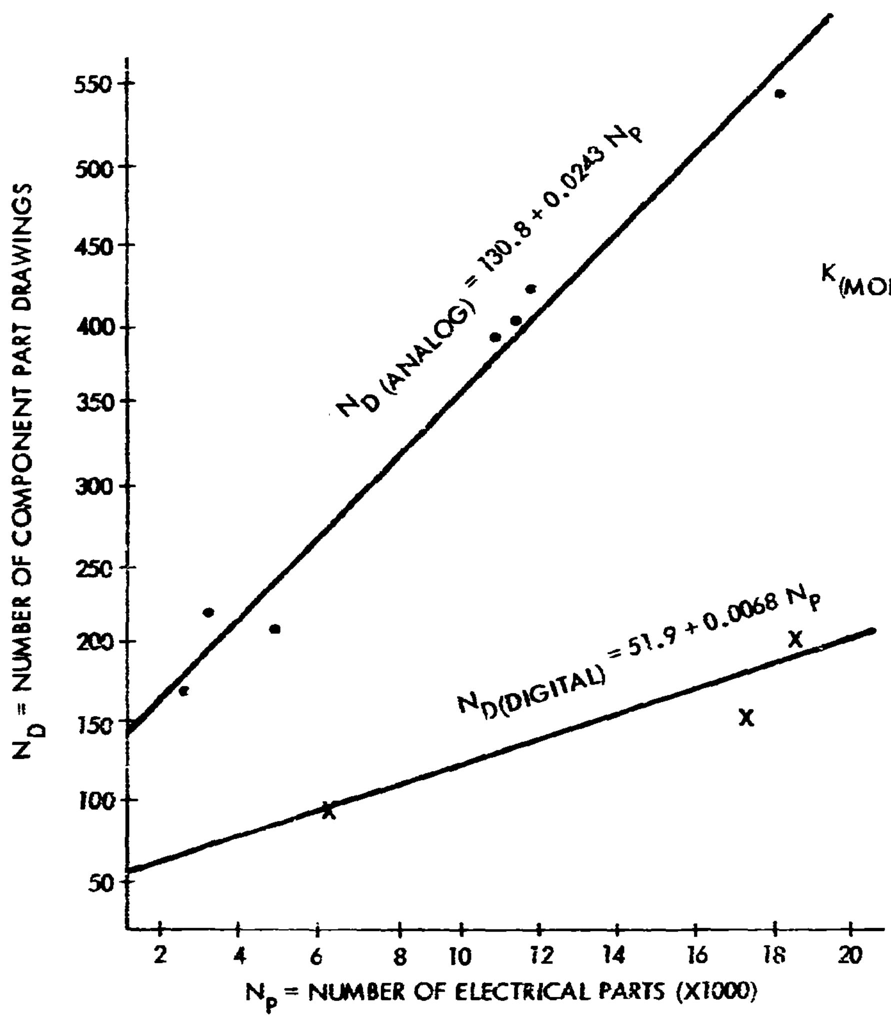
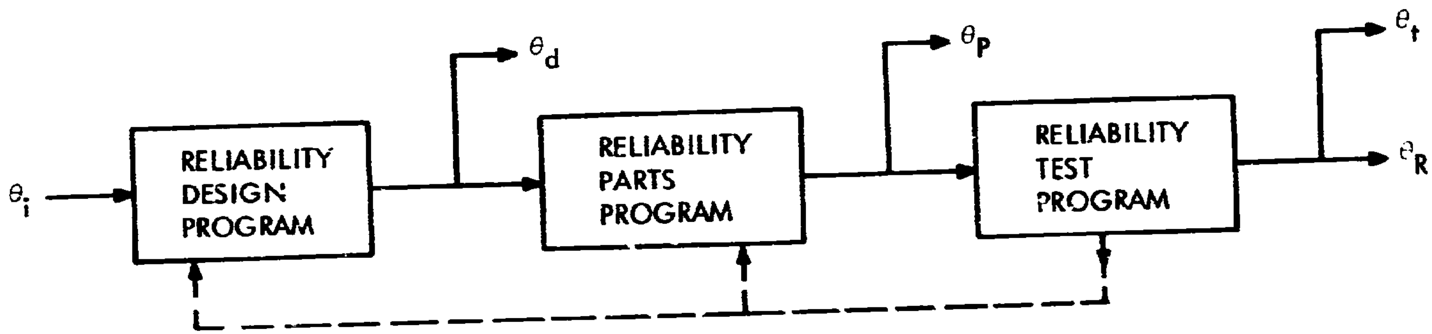


Figure 1. Equipment Code vs Development Time Span



$$K_{(MODIFIER)} = \frac{N_{DA}}{N_{DD}} = \frac{130.8 + 0.0243\ N_p}{51.9 + 0.0068\ N_p}$$

Figure 2. Comparison of Analog vs Digital Equipment



θ_i = EFFECTIVE ACHIEVED MTBF WITHOUT RELIABILITY PROGRAM

θ_d = EFFECTIVE ACHIEVED MTBF RESULTING FROM RELIABILITY DESIGN PROGRAM

θ_P = EFFECTIVE ACHIEVED MTBF RESULTING FROM DESIGN PLUS PARTS PROGRAM

$\theta_t = \theta_R$ MTBF RESULTING FROM DESIGN PLUS PARTS PLUS TEST PROGRAM

-----CORRECTIVE ACTION FEEDBACK LOOPS

Figure 3. Reliability Program Conducted on RDT&E Phase of Program E

SECTION III

ANALYSES

1. ANALYTICAL APPROACH

Two basic approaches employing the same analytical techniques have been used in this study to quantify reliability as a function of cost. Both of these approaches involve multiple regression analysis using the least squares fitting technique.

The first approach was to relate resultant equipment reliability (MTBF) to the reliability element costs (incorporating normalization factors as discussed previously). This analysis effort utilized resultant measured equipment reliability (MTBF) converted to a 60 percent lower confidence level (LCL) and cost data by element. The cost data was collected in terms of dollars and converted to mandays using average AESD manday rates applicable during the development time period for the particular equipment. Figure 2 of Section II shows the development time spans for the equipments in the study. The reliability manpower associated with each program is shown in Table III.

The second approach was to relate the reliability contribution of each reliability element to the cost of performing that reliability element (this is the same cost base described above). As indicated in Section II, historical failure rate data and Engineering assessment were used to determine the improvement in equipment MTBF as a result of the contribution of each of the reliability elements. This analysis also allowed the determination of the MTBF (θ_i) that the equipment would have achieved without the benefit of any reliability effort.

2. ANALYTICAL MODELS

It was assumed that the relationships between cost and reliability could be explained by linear equations of the following form:

$$\theta_{Ri} = \beta_0 + \beta_1 C_{1i} + \beta_2 C_{2i} + \beta_3 C_{3i} + \dots + \beta_p C_{pi}$$
$$+ \beta_{p+1} X_{1i} + \dots + \beta_{p+k} X_{ki} + e_i \qquad (1)$$

where:

θ_{Ri} = resultant equipment MTBF (hours)

C_{pi} = reliability element cost (mandays)

X_{ki} = other prediction parameters

β_p, β_{p+k} = regression coefficients to be determined

e_i = random variation of observations (normally distributed with constant standard deviation for all combinations of independent variable values)

$$C_i = \alpha + \beta_1 \theta_{Ri} + \beta_2 X_{1i} + \ldots + \beta_{1+k} X_{ki} + e_i \quad (2)$$

where:

C_i = reliability element cost (mandays)

θ_{Ri} = resultant equipment MTBF (hours)

X_{ki} = other prediction parameters

α's, β's = regression coefficients to be determined

e_i = random error (normally distributed)

$$\theta_{Ei} = \alpha + \beta_1 C_i + \beta_2 X_{1i} + \ldots + \beta_{1+k} X_{ki} + e_i \quad (3)$$

where:

θ_{Ei} = elemental reliability worth (MTBF in hours)

C_i = reliability element cost (mandays)

X_{ki} = other prediction variables

α's, β's = regression coefficients to be determined

e_i = random error (normally distributed)

The form of these models is linear with respect to the regression coefficients but not necessarily linear with respect to the independent variables. This linear condition allows the use of a least squares procedure for estimating the regression coefficients.

A multiple regression program called MUL-REGRESSION (see Appendix A) within the GE-developed statistical time-share program STATSYST*** was used to estimate the coefficients and obtain goodness of fit indications such as student-t statistics, F-ratios, standard deviations, standard error of estimates and various correlation statistics. These indicators were used to perform significance tests in order to assure that enough independent variables were included to account for a significant amount of the error. Also, they were used to justify excluding the prediction variables that did not make a significant contribution to error elimination.

SECTION IV

RESULTS OF ANALYSES

1. GENERAL

It must be pointed out that the following results are based on analyses of data collected on ten equipments from two manufacturers. Consequently, because of the limited nature of the data base, caution must be exercised in utilization of the results. Specifically, caution must be taken to apply equations presented within the bounds of the data from which the equations were generated. Section II summarizes the data base for the study and should be used as a guide for the range of use of the equations.

The results presented in this section are divided into two categories. The first category is termed Gross Prediction Equations and represents results derived from factual equipment characterization and cost data. The second category is termed Allocation Equations and represents results derived from assessment of historical failure rate data. Consequently, the latter equations are less rigorous than the former.

2. GROSS PREDICTION EQUATIONS

Multiple regression analyses[2] were performed to develop prediction equations for:

- Total reliability cost as a function of resultant equipment MTBF and quantity of parts.
- Reliability prediction[3] cost as a function of quantity of parts.
- Reliability design review[3] cost as a function of quantity of parts.
- Reliability failure modes and effects analysis cost as a function of the prediction cost.
- Reliability design cost as a function of quantity of parts.

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[2] See Appendix A.

[3] Note that prediction and design reviews are mandatory per MIL-STD-785 and design review and prediction are directly relatable to equipment complexity.

- Resultant equipment MTBF as a function of reliability parts program cost, reliability test program cost and quantity of parts.

All of the cost data used in developing these relationships was normalized as described in Section II prior to performing the analyses.

It should also be pointed out that a formal failure modes and effects analysis effort was performed for only three of the equipments in the data base. Therefore, the prediction relationship for failure modes and effects analysis cost, being developed from only three pieces of data, is statistically weaker than the others. Also, since there were only three equipments with FMEA, these equipments were excluded from the development of the prediction equation for the reliability design cost.

The prediction equations are:

Total Reliability Cost

$$C_T = 1.804\left(\theta_R^{0.370}\right)\left(N_p^{0.684}\right) \tag{4}$$

Reliability Prediction Cost

$$C_{PR} = 119.16 + 0.096N_p \tag{5}$$

Reliability Design Review Cost

$$C_{DR} = 92.479 + 0.022N_p \tag{6}$$

Reliability Failure Modes and Effects Analysis Cost

$$C_{FM} = 0.80\ C_{PR} \tag{7}$$

Reliability Design Cost (by definition)

$$C_d = C_{PR} + C_{DR} + C_{FM} \tag{8}$$

Reliability Design Cost (excluding FMEA)

$$C_d' = 242.2 + 0.121\ N_p \tag{8a}$$

Reliability Parts Program Cost plus Reliability Test Program Cost

$$C_{p+t} = C_T - C_d \tag{9}$$

Resultant Equipment MTBF

$$\theta_R = \frac{5.36\left(C_P^{1.42}\right)\left(C_t^{0.64}\right)}{N_p^{1.37}} \tag{10}$$

A summary of the key statistics for these equations is shown in Table V for equations (4), (5), (6), (7), (8a) and (10). Equations (8) and (9) are not included in the summary since they were generated by definition instead of by performing regression analyses.

These equations allow prediction of reliability costs and resultant equipment MTBF. Assessment of the contribution of the reliability element costs to the resultant equipment MTBF is also provided. The contribution of the reliability elements to equipment MTBF is addressed in greater detail later in this report; therefore, these equations have been termed gross prediction equations.

a. Adequacy of Prediction Equations

The statistics provided through the regression analyses give an indication of the accuracy of the equations. As can be seen from Table V, the index of determination, R^2, indicates that the least accurate prediction equation accounts for approximately 48 percent of the initial variation. Also, from Table V, a comparison of the standard error of estimate, S_E, and the standard deviation, S_Y, indicates the adequacy of the equations.

Also, the adequacy of these prediction equations can be assessed by comparing the values predicted by each equation with the actual data values that were used to develop the relationships (see Table VI). Figures 4 through 11 show plots of the predicted values vs the actual values for equations (4) through (10). The solid line in these plots is the line of perfect fit.

In addition to percent difference between predicted and actual values, confidence limits about the actual average values can be computed by multiplying the predicted values by the appropriate factor. Multiplying factors for 60, 75 and 95 percent confidence limits are shown in Table VII for each of the allocation equations. These multiplying factors assume a normal distribution and the closer they are to 1.00, the narrower the limits and the more precise the estimate. The more the values of the dependent variables of the new equipment deviate from the average of the data base, the wider the limits will be.

TABLE V. GROSS PREDICTION EQUATIONS AND STATISTICS SUMMARY

Equation	R	R^2	F Ratio	S_E	S_Y
$C_T = 1.80 \left(\theta_R^{0.37}\right)\left(N_p^{0.68}\right)$	0.978	0.957	99.99	0.180	0.759
$C_{PR} = 119.16 + 0.096\, N_p$	0.699	0.488	97.55	679.29	895.54
$C_{DR} = 92.46 + 0.02\, N_p$	0.759	0.576	98.91	132.37	191.70
$C_{FM} = 0.80\, C_{PR}$	0.996	0.992	99.62	160.77	1513.29
$C_d' = 242.2 + 0.121\, N_p$	0.936	0.876	99.80	286.53	740.34
$\theta_R = \dfrac{5.36\left(C_p^{1.42}\right)\left(C_t^{0.64}\right)}{N_p^{1.37}}$	0.895	0.801	98.43	0.879	0.479

where:

R = correlation coefficient, i.e., how well does the data fit the equation (1.0 = perfect fit)

R^2 = index of determination, the percent of the variation due to the regression $(1 - R^2)$

F Ratio = % probability that the regression line truly expresses the data (% value)

S_E = standard error of estimate $\left[\Sigma(y_i - \hat{y}_i)^2/(n-2)\right]^{1/2}$

S_Y = standard deviation $\left[\Sigma(y_i - \bar{y})^2/(n-1)\right]^{1/2}$ about the mean

TABLE VI. COMPARISON BETWEEN PREDICTED COSTS AND ACTUAL COSTS WITH PERCENT DIFFERENCE

		Equipment Letter Code									
		A	B	C	D	E	F	G	H	J	K
C_T	Pred.	21,561	7,636.8	7,352.5	2,925.3	9,026.8	7,077.1	2,391.9	11,621.7	2,664.8	2,817.7
	Act.	23,449	10,264.0	7,719.0	2,976.0	6,776.0	5,883.0	2,645.0	11,947.0	2,532.0	2,795.0
	% Diff.	-8.75	-34.40	-4.98	-1.73	24.93	16.87	-10.58	2.80	4.98	0.81
C_{PR}	Pred.	1,894.8	1,145.5	1,189.2	371.5	1,806.6	714.7	562.9	1,781.4	411.8	367.7
	Act.	3,165	1,036	761	452.0	487.0	649.0	549.0	2,076.0	527.0	544.0
	% Diff.	-67.03	9.56	36.01	-21.66	73.04	9.19	2.47	-16.54	-27.98	-47.94
C_{DR}	Pred.	505.3	331.1	341.2	151.1	484.8	231.0	195.6	478.9	160.5	150.2
	Act.	633.6	460.0	326.0	206.0	203.0	131.2	165.0	594.0	148.0	163.0
	% Diff.	-25.39	-38.93	4.45	-36.33	58.12	43.20	15.64	-24.03	7.78	-8.50
C_{FM}	Pred.	2,529.3	-	-	-	389.2	519.1	-	-	-	-
	Act.	2,531.2	-	-	-	203.0	649.0	-	-	-	-
	% Diff.	-0.07	-	-	-	47.84	-25.02	-	-	-	-
C_d	Pred.	4,924.4	1,476.6	1,530.4	522.6	2,680.6	1,464.8	758.5	2,260.3	572.3	517.9
	Act.	6,329.8	1,496.0	1,087.0	658.0	893.0	1,429.2	714.0	2,670.0	675.0	707.0
	% Diff.	-28.41	-1.31	28.97	-25.91	66.68	2.43	5.86	-18.13	-17.95	-36.52
C_d'	Pred.	-	1,538.6	1,593.8	560.9	-	-	802.7	2,342.0	611.8	556.3
	Act.	-	1,496.0	1,087.0	658.0	-	-	713.0	2,670.0	675.1	707.0
	% Diff.	-	2.77	31.80	-17.30	-	-	11.18	-14.01	-10.34	-27.10
C_{p+t}	Pred.	16,631.7	6,160.2	5,849.1	2,402.7	6,346.8	5,612.3	1,634.0	9,361.4	2,092.5	2,299.8
	Act.	17,119.6	8,768	6,632.0	2,318.0	5,883.0	4,456.2	1,932.0	9,277.0	1,856.8	2,088.0
	% Diff.	-2.93	-42.33	-13.38	3.52	7.31	20.59	-18.24	0.90	11.26	9.21
C_R	Pred.	1,121.2	479.9	181.6	197.3	98.5	289.4	78.6	343.8	127.2	199.3
	Act.	1,350.0	225.0	188.0	225.0	141.0	501.0	46.0	287.0	133.9	207.0
	% Diff.	-20.41	53.12	-3.52	-14.04	-43.15	-73.11	41.47	16.52	-4.55	-3.86

Note: Equations summarized in Table V.

TABLE VII. CONFIDENCE LIMIT MULTIPLYING FACTORS

Prediction Variable	$M_{0.60}$		$M_{0.75}$		$M_{0.95}$	
	Lower	Upper	Lower	Upper	Lower	Upper
C_T	0.950	1.052	0.931	1.070	0.674	1.140
C_{PR}	0.813	1.186	0.739	1.260	0.516	1.480
C_{DR}	0.877	1.120	0.828	1.170	0.681	1.320
C_{FM}	0.841	1.156	0.725	1.275	0.445	2.450
C_d^1	0.913	1.087	0.878	1.123	0.757	1.243
θ_R	0.871	1.147	0.821	1.212	0.689	1.450

As can be seen from Table VI and Figure 5, the largest deviation for the predicted values was the reliability prediction cost for radar E which was high by a factor of almost four. Also, the design is high by a factor of three. This results from the fact that the actual reliability prediction and design costs for this equipment are low. The reason they are low is attributed to the fact that this radar was developed in parallel with the digital portion of the same system. This is digital equipment F in the data base. It appears that the radar benefitted from this parallel development, which results in a lower cost in prediction and design due to commonality of tasks. If equipment E is excluded from the reliability prediction analysis, the index of determination, R^2, increases from 0.488 to 0.812 and the standard error of estimate decreases from 679.29 to 430.05.

All of the other prediction equations yield predicted values that are from 0.5 to 2 times the actual values. It is felt that this is acceptable for initial estimates based on the limited data base available coupled with general equipment development uncertainty.

b. Using the Gross Prediction Equations

The gross prediction equations have two purposes:

(1) To predict the total reliability cost, C_T, required to achieve a given MTBF requirement, θ_R.

(2) To predict the achievable reliability, θ_R, by the expenditure of certain levels of resources on given reliability program elements.

For analog equipments, the first purpose can be realized through the direct use of equation (4). In addition, equations (5), (6), (7), and (8a) can be utilized to break out design cost. In order to approximately isolate parts and test costs, equation (10) can be used with θ_R equal to the requirement MTBF as described later.

For digital equipments, define C_{p+t} using equations (4) through (9) as required. Then, using equation (10) with θ_R equal to the requirement MTBF, determine the values of C_p and C_t. The value of C_p divided by K yields the digital parts cost. Next, divide the value obtained for C_d (or C_d' as applicable) by K. The total cost C_T for digital equipments is then equal to

$$\frac{C_d}{K} + \frac{C_p}{K} + C_t$$

To achieve the second purpose, where a given dollar figure is allotted to the reliability effort and it is desired to determine the reliability achievable and the necessary resource allocations to be made to each of the reliability elements, use the following procedure. Equations (5), (6), (7), (8), (8a) are used to define the fixed design costs. Then equation (10) is utilized with various combinations of C_p and C_t to determine the resulting values of reliability possible. Again, modifying factors for digital equipments must be used as required on the various cost parameters.

A specific example of this application of equation (10) is portrayed in Figure 12. In this example, the resultant equipment MTBF requirement is chosen to be 188 hours, the quantity of parts, N_p, is chosen to be 11,160, the total reliability program cost is predicted from equation (4) to be 7,385 mandays (MD), constant for this example, and the reliability design program cost is predicted from equations (5), (6), (7) and (8) to be 1,518 MD's. From equation (9), this leaves 5,867 MD's to be divided between the reliability parts program and the reliability test program. The curve of Figure 12 is obtained by varying the parts cost to test cost ratio, while holding the total cost for these two elements constant at 5,867 MD's. The solid portion of the curve shows the range of the data base of the study. The asterisks show the 60-percent confidence limits[4] about the data points.

As can be seen from the gross prediction equations, one would expect approximately 1.5 times as much to be spent in parts as in test to obtain the maximum MTBF. The data base for the 10 equipments shows that 1.2 times as much, on the average, was spent in parts as in test. This represents the initial parts cost. The remainder of the parts cost, which results from test feedback (see Figure 3) is included in test cost. This feedback parts cost is made more obvious in the next section through incremental gain assessment, where it is shown that, as test cost increases, the ratio of parts cost to test cost decreases and the MTBF increases. Therefore, in actual practice, more will be spent in test than in parts.

Furthermore, there is a range of MTBF's that can be achieved for a specified equipment depending on the amount of dollars expended and the design constraints that are within the state of the art. Therefore, equation (4) can be used to develop a relationship to assess the impact on the increase in cost as a function of the increase in MTBF expressed as a ratio of the desired MTBF vs minimum MTBF. Using equation (4)

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[4] A confidence band (or limits) on the mean of the dependent variable for a specified set of values of the independent variables (data points) is an interval which one can state with a specified degree of confidence contains the true mean (or long range average) value of the dependent variable (Ref. 3).

$$\frac{C_{Ta}}{C_{Tb}} = \frac{1.804}{1.804}\left(\frac{\theta_a^{0.370}}{\theta_b^{0.370}}\right)\left(\frac{N_p^{0.684}}{N_p^{0.684}}\right)$$

where

C_{Ta} = cost (normalized and expressed in mandays required to achieve θ_a

C_{Tb} = cost (normalized and expressed in mandays required to achieve θ_b

θ_a = desired MTBF within the state of the art

θ_b = minimum MTBF within the state of the art

If N_p is constant

$$\frac{C_{Ta}}{C_{Tb}} = \left(\frac{\theta_a}{\theta_b}\right)^{0.370}$$

This relationship has been used to produce the curve shown in Figure 12a. This curve can be used to obtain increase in cost as a result of an increase in MTBF.

3. ALLOCATION EQUATIONS

This paragraph details the effort set forth to quantize the reliability contribution of each reliability element in terms of MTBF hours as function of cost.

The first step toward establishing relationships between reliability and cost using the data from Section II was to develop a usable starting point relationship involving initial MTBF (see Figure 13). This initial MTBF is the reliability of the equipment that would be realized without any reliability effort being applied. A multiple regression was performed and a prediction equation for θ_i was developed in terms of the equivalent analog quantity of electrical parts (N_{PK}). The normalization factor used here was three since the average part failure rate for the analog equipments was approximately three times the average part failure rate for the digital equipments of the 10 equipments in the data base. The equation is:

$$\theta_i = 1.061 \times 10^4 / N_{PK}^{0.921}$$

and is plotted in Figure 13.

Next, effective cumulative reliability MTBF relationships were developed by performing regression analyses using the cumulative reliability element MTBF's as the dependent variable and the individual normalized reliability element costs along with the previous cumulative reliability element MTBF's as the independent variables (see Figure 14). The data for the 10 equipments is summarized in Tables III and IV.

MTBF gain relationships were also developed using the same data. The gains, MTBF out divided by MTBF in (see Figure 14), were used as the dependent variables and the normalized reliability element costs were used as independent variables. These MTBF and gain equations along with the key statistics are summarized in Table VIII. Plots of the gain equations are shown in Figure 15.

a. Adequacy of the Allocation Equations

The statistics provided through the regression analyses give an indication of the accuracy of the equations. As can be seen from Table VIII the index of determination, R^2, indicates that the prediction equations account for a significant amount of the initial variation. Also from Table VIII, a comparison of the standard error of estimates, S_E, and the standard deviations, S_Y, indicates the adequacy of the equations.

The adequacy of these equations can be assessed by comparing the values predicted by the equations with the actual data values for each equipment that was used to develop the relationships. This comparison can be seen in Tables IX and X. Figures 16 through 23 are plots of the predicted values vs the actual values. The solid line in these plots is the line of perfect fit.

In addition to percent difference between predicted and actual values, confidence limits about the actual average values can be computed by multiplying the predicted values by the appropriate factor. Multiplying factors for 60, 75 and 95 percent confidence limits are shown in Table XI for each of the allocation equations. These multiplying factors assume a normal distribution; the closer they are to 1.00 the narrower the limits and the more precise the estimate. The more the values of the dependent variables of the new equipment deviate from the average of the data base the wider the limits will be.

TABLE VIII. MTBF GAIN EQUATIONS WITH STATISTICS SUMMARY

Equation	R	R^2	F Ratio	S_E	S_Y
$\theta_i = \frac{1.060 \times 10^4}{N_{PK}^{0.921}}$ (Initial MTBF)	0.815	0.664	99.59	0.508	0.828
$\theta_d = 0.211\left(\theta_i^{0.956}\right)\left(C_d^{0.300}\right)$ (Design MTBF)	0.970	0.941	99.99	0.234	0.846
$\theta_p = 0.585\left(\theta_d^{1.134}\right)\left(C_p^{0.185}\right)$ (Design+ Parts MTBF)	0.972	0.944	99.99	0.226	1.004
$\theta_t = 0.094\left(\theta_p^{0.683}\right)\left(C_t^{0.741}\right)$ (Design+ Parts + Test MTBF)	0.957	0.916	99.98	0.283	0.879
$G_d = 0.302\left(C_d^{0.247}\right)$ (Design Gain)	0.735	0.540	98.45	0.177	0.246
$G_p = 1.145\left(C_p^{0.137}\right)$ (Parts Gain)	0.537	0.288	89.08	0.191	0.214
$G_t = 0.0064\left(C_t^{0.952}\right)$ (Test Gain)	0.845	0.714	99.79	0.480	0.845

R = correlation coefficient, how well does the data fit the equation (1.0 = perfect fit).

R^2 = index of determination, the percent of the variation due to the regression $(1 - R^2)$.

F Ratio = % probability that the regression line truly expresses the data (% value).

S_E = standard error of estimate $[\Sigma(y_i - \hat{y}_i)^2/(n-2)]^{1/2}$

S_Y = standard deviation $[\Sigma(y_i - \bar{y})^2/(n-1)]^{1/2}$ about the mean

TABLE IX. COMPARISON BETWEEN PREDICTED MTBF'S AND ACTUAL MTBF'S WITH PERCENT DIFFERENCE

		Equipment Letter Code									
		A	B	C	D	E	F	G	H	J	K
θ_i	Pred.	3.6	2.1	1.98	7.5	1.3	9.9	4.5	3.6	6.5	7.6
	Act.	7.0	2.0	3.0	5.0	1.0	11.0	5.0	2.0	3.5	15.0
	% Diff.	-94.4	4.76	-51.51	33.33	23.07	-11.11	-11.11	44.44	46.15	-97.36
θ_d	Pred.	18.7	3.7	4.9	6.9	1.6	18.5	7.0	4.4	4.9	20.1
	Act.	20.0	3.0	5.0	8.0	1.5	15.0	8.0	5.0	7.0	22.0
	% Diff.	-6.95	18.91	-2.04	-15.94	6.25	18.91	-14.28	-13.63	-42.05	-9.45
θ_p	Pred.	99.4	9.4	15.0	22.1	3.9	53.5	22.6	18.1	19.2	71.6
	Act.	95.0	11.0	16.0	26.0	4.0	67.0	20.0	15.0	25.0	60.0
	% Diff.	4.42	-17.02	-6.66	-17.64	-2.56	-25.23	11.50	17.12	-30.20	16.2
θ_t	Pred.	1,173.0	255.0	315.0	180.0	100.0	460.0	105.0	243.0	121.0	246.0
	Act.	1,350.0	225.0	188.0	225.0	141.0	501.0	46.0	287.0	133.0	209.0
	% Diff.	-15.08	11.76	40.31	-25.0	-41.0	-8.91	56.19	-18.10	9.91	15.04

Note: Equations summarized in Table VIII.

TABLE X. COMPARISON BETWEEN PREDICTED AND ACTUAL GAINS WITH PERCENT DIFFERENCE

		Equipment Letter Code									
		A	B	C	D	E	F	G	H	J	K
G_d	Pred.	2.6	1.8	1.69	1.5	1.6	1.8	1.5	2.1	1.5	1.50
	Act.	2.9	1.5	1.66	1.6	1.5	1.4	1.6	2.5	2.0	1.46
	% Diff.	-11.53	16.66	1.77	-6.66	6.25	22.22	-6.66	-19.04	-33.33	2.66
G_p	Pred.	4.1	3.6	3.3	2.9	3.3	3.3	3.0	3.8	3.6	3.0
	Act.	4.7	3.7	3.0	3.3	2.6	4.5	2.5	3.0	2.9	2.5
	% Diff.	-14.63	-2.77	9.09	-13.79	21.21	-36.36	16.66	21.05	19.44	16.66
G_t	Pred.	21.6	20.2	18.1	6.0	14.8	8.8	3.9	14.5	3.8	4.3
	Act.	14.2	20.5	11.8	8.6	35.2	7.5	2.3	19.1	5.3	3.5
	% Diff.	34.25	-1.48	34.80	-43.33	-137.83	14.77	41.02	-31.72	-39.47	18.60
G_T	Pred.	235.5	132.0	106.0	27.0	79.7	53.6	18.0	116.0	17.0	20.0
	Act.	192.8	112.0	63.0	45.0	141.0	45.5	9.2	144.0	38.0	14.0
	% Diff.	18.13	15.15	40.56	-66.66	-76.91	15.11	48.88	-24.13	-123.52	30.0

Note: Equations summarized in Table VIII.

TABLE XI. CONFIDENCE LIMIT MULTIPLYING FACTORS

Prediction Variable	$M_{0.60}$		$M_{0.75}$		$M_{0.95}$	
	Lower	Upper	Lower	Upper	Lower	Upper
θ_i	0.862	1.15	0.819	1.22	0.690	1.43
θ_d	0.935	1.07	0.910	1.09	0.834	1.19
θ_p	0.925	1.08	0.903	1.11	0.819	1.22
θ_t	0.921	1.09	0.891	1.12	0.806	1.24
G_d	0.947	1.05	0.929	1.07	0.878	1.14
G_p	0.946	1.05	0.927	1.08	0.870	1.15
G_t	0.893	1.14	0.829	1.21	0.706	1.42

Note: *Equations summarized in Table VIII.*

b. Using the Allocation Equations

In summary, the allocation equations developed in this study are as follows:

$$\theta_i = (1.061 \times 10^4)/N_{PK}^{0.921} \tag{11}$$

$$\theta_d = 0.211\left(\theta_i^{0.956}\right)\left(C_b^{0.300}\right) \tag{12}$$

$$\theta_d = 0.585\left(\theta_d^{1.134}\right)\left(C_p^{0.185}\right) \tag{13}$$

$$\theta_t = 0.094\left(\theta_p^{0.683}\right)\left(C_t^{0.741}\right) \tag{14}$$

$$G_d = 0.302\left(C_d^{0.247}\right) \tag{15}$$

$$G_p = 1.145\left(C_p^{0.137}\right) \tag{16}$$

$$G_t = 0.0064\left(C_t^{0.952}\right) \tag{17}$$

$$G_T = (G_d)(G_p)(G_t) \tag{18}$$

Equation (11) can be used to estimate the initial MTBF prior to performing any reliability effort. To use equation (11), the number of electrical parts must be normalized to an analog level. This is done for digital equipments by dividing the estimate of the number of electrical components by three.

Equations (12) through (14) can be used to predict the cumulative MTBF contribution due to the various reliability elements. Specifically, since these equations were developed independently of each other using the data base of Section II, the output of equation (11) can be used in equation (12) to predict the cumulative MTBF after the reliability design effort; the output from equation (12) can be used in equation (13) to predict the cumulative MTBF after the reliability design plus parts effort; and the output from equation (13) can be used in equation (14) to predict the cumulative MTBF after the reliability design plus parts plus test effort. This output of equation (14) is also the predicted resultant MTBF for the equipment. This approach yields a predicted MTBF that is dependent on the total reliability cost chosen and how it is spread among the reliability elements. On the average, for the 10 equipments in the study, 22 percent of the cost was put into design, 40 percent into parts and 38 percent into test. A little later in this section, the gain relationships will be used to assess the effect on equipment reliability as a result of varying these percentages.

If one is interested in a prediction of the MTBF contribution of each of the individual reliability elements, these can be obtained by subtracting θ_i from θ_d to get the design contribution; by subtracting θ_d from θ_p to get the parts contribution; and by subtracting θ_p from θ_t to get the test contribution.

Equations (15) through (17) can be used to predict the reliability gain, i.e., the times improvement in MTBF as a function of the reliability element costs. Specifically, selected costs for each reliability element can be used in equations (15), (16) and (17) to predict the element MTBF gains.

Further, as indicated in equation (18), these gain equations can be multiplied together to yield an expression for total gain in terms of the reliability element cost. When this is done, equation (18) can be written as:

$$G_T = 0.0021\left(C_d^{0.247} C_p^{0.137} C_t^{0.952}\right) \qquad (19)$$

Multiplying and dividing each term on the right side by C_T, the total cost, it follows that:

$$G_T = 0.0021\left[\left(\frac{C_d}{C_T}\right)^{0.247} \left(\frac{C_p}{C_T}\right)^{0.137} \left(\frac{C_t}{C_T}\right)^{0.952} \left(C_T\right)^{1.336}\right] \qquad (20)$$

This equation now can be used to assess the impact of changing the distribution of total effort within the reliability elements. This is done by determining a total reliability cost. For example, if desired as a first cut, equation (4) can be used for this purpose. This cost is then divided among the reliability elements in keeping with the average of the 10 equipments in the study. By holding the total cost in the equation constant while varying the ratios of the element-cost-to-total cost over the data range, the effect on total gain can be observed. In doing this, the sum of reliability element cost ratios in the equation must always equal one. For example, if 50 percent of the cost is put in test and 30 percent in parts, then 20 percent must be put in design. A display of such an assessment of varying reliability element costs is shown in Figure 24 for a total cost of 7680 man-days which represents the average of the total cost for the 10 equipments in the study. The rectangle in the figure represents the range of the data. The vertical and the horizontal axes represent the percent of total cost in parts and test respectively. The diagonal lines represent the percentage of total cost in design. The contour lines represent constant total gain lines for varying percentage distributions of the three reliability elements. As can be seen from Figure 24, test is the most effective single element. Also the most optimum gain within the range of the data is obtained when twice as much effort is expended in test as in parts. Perhaps this ratio should be even higher but the limited range of data in this study does not allow speculation beyond the 2 to 1 ratio.

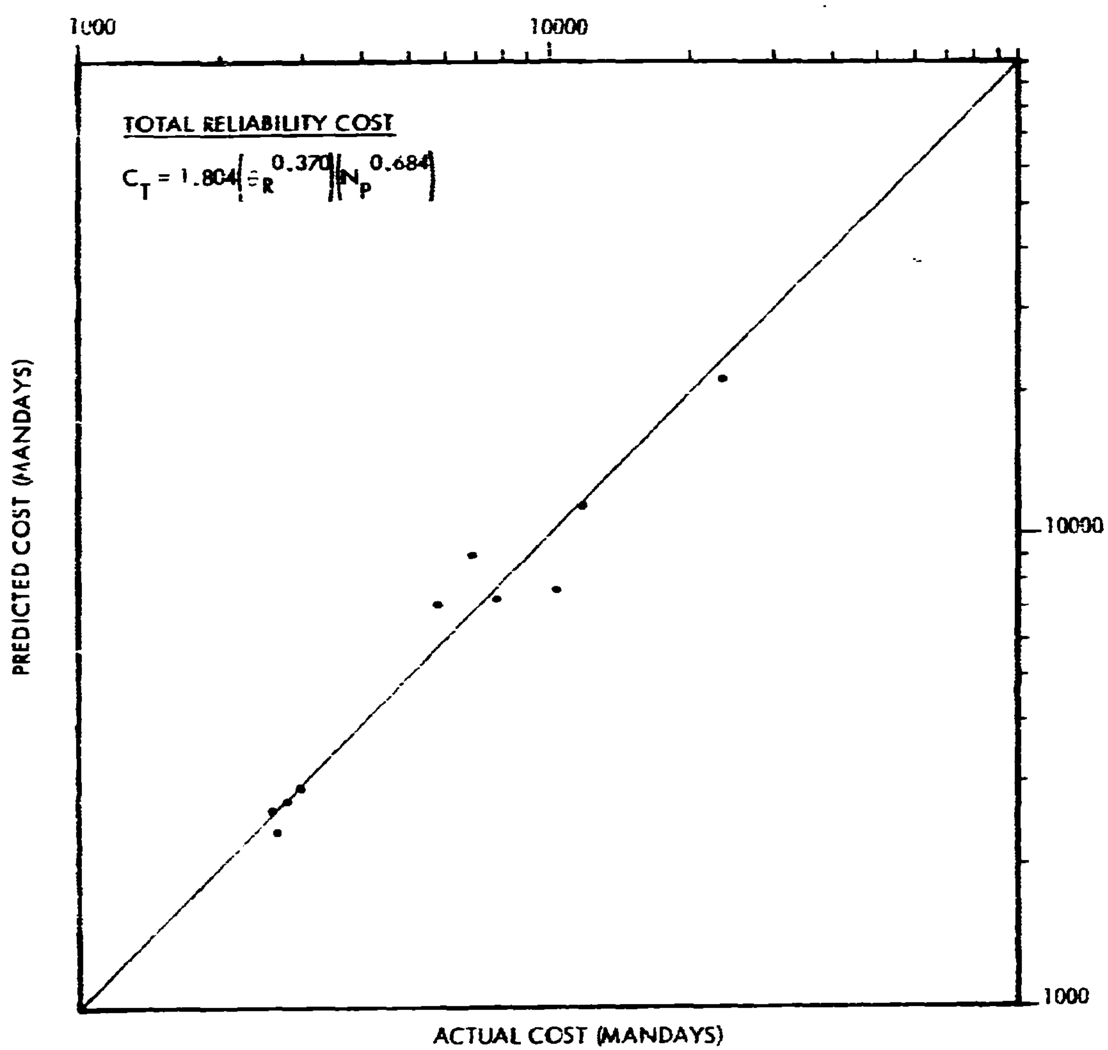


Figure 4. Predicted Total R Cost vs Actual Total R Cost

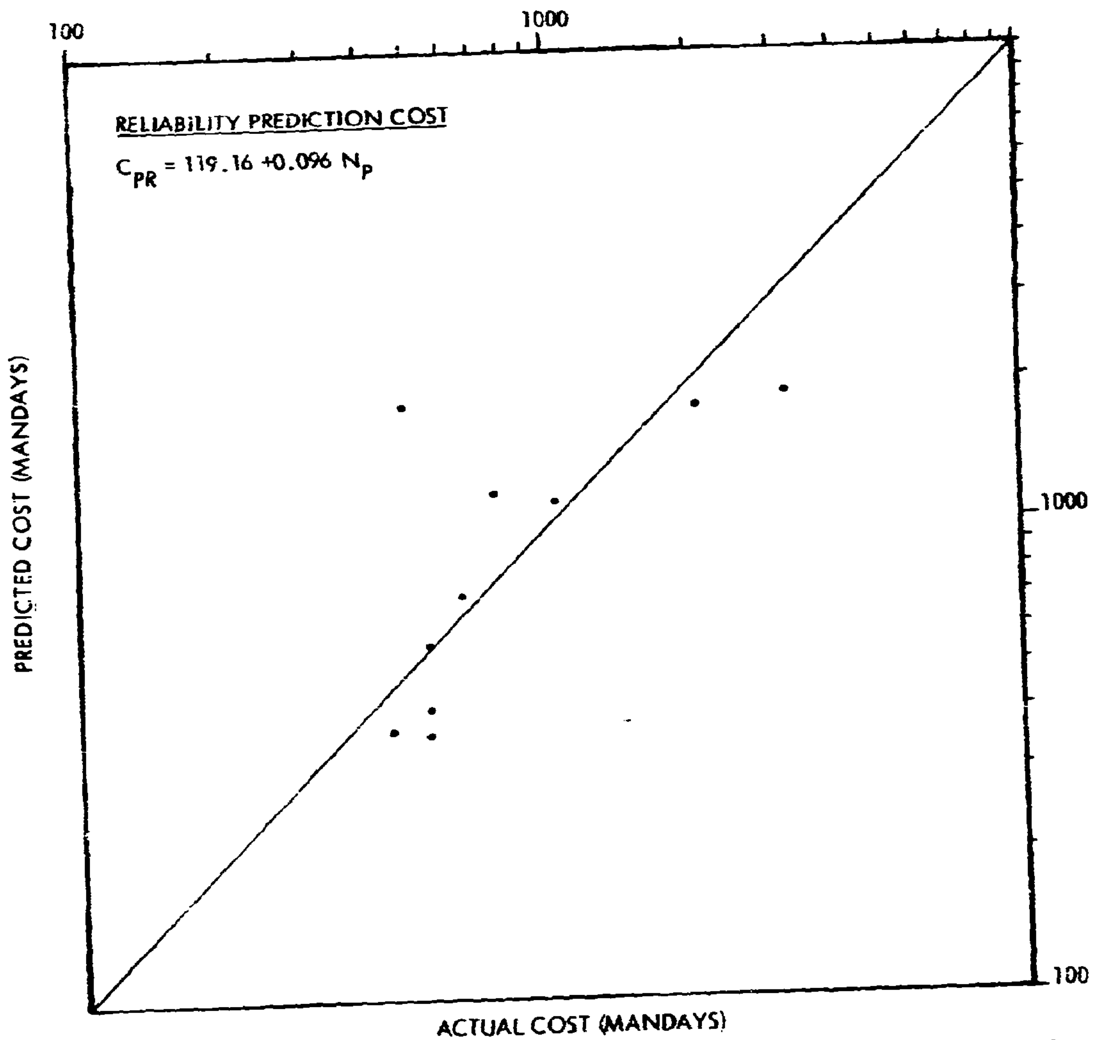


Figure 5. **Predicted R Prediction Cost vs Actual R Prediction Cost**

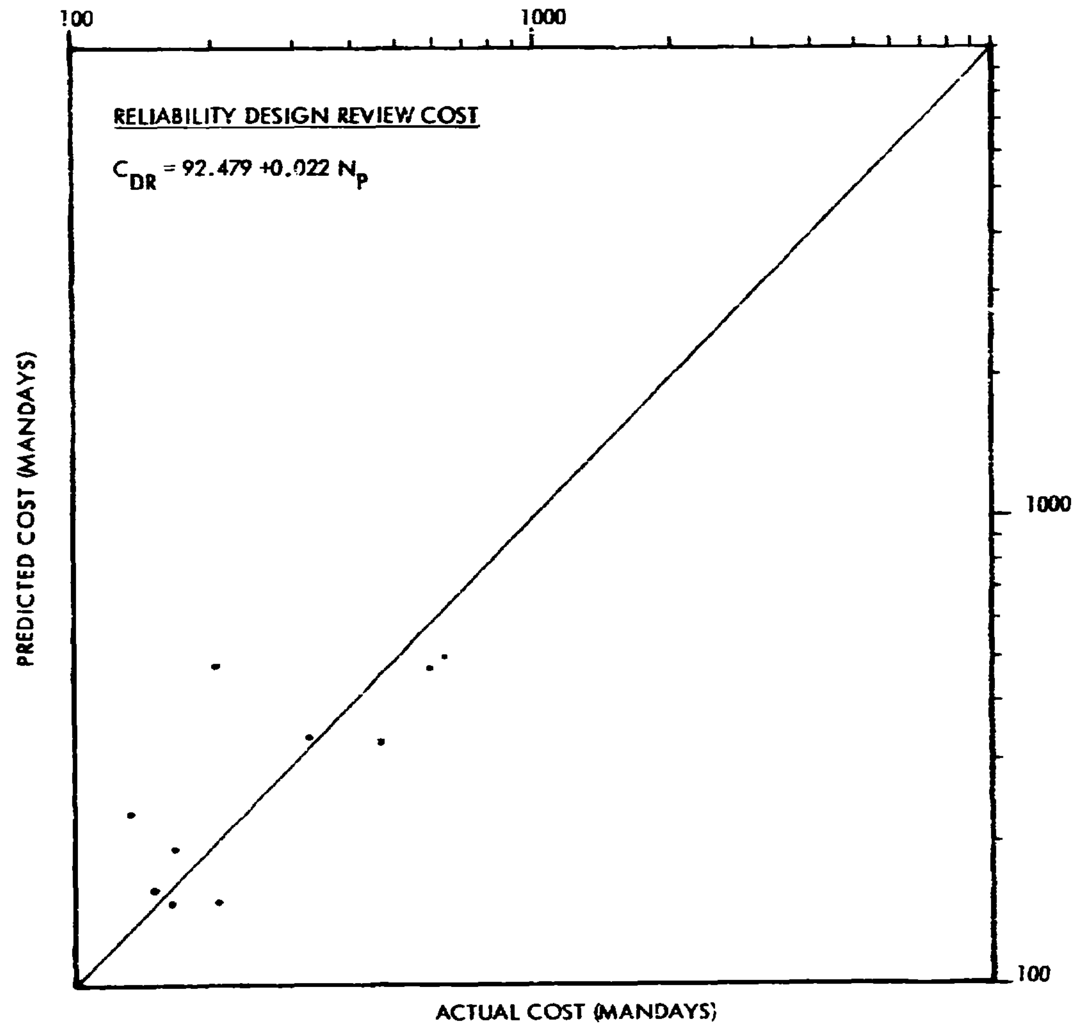


Figure 6. Predicted R Design Review Cost vs Actual R Design Review Cost

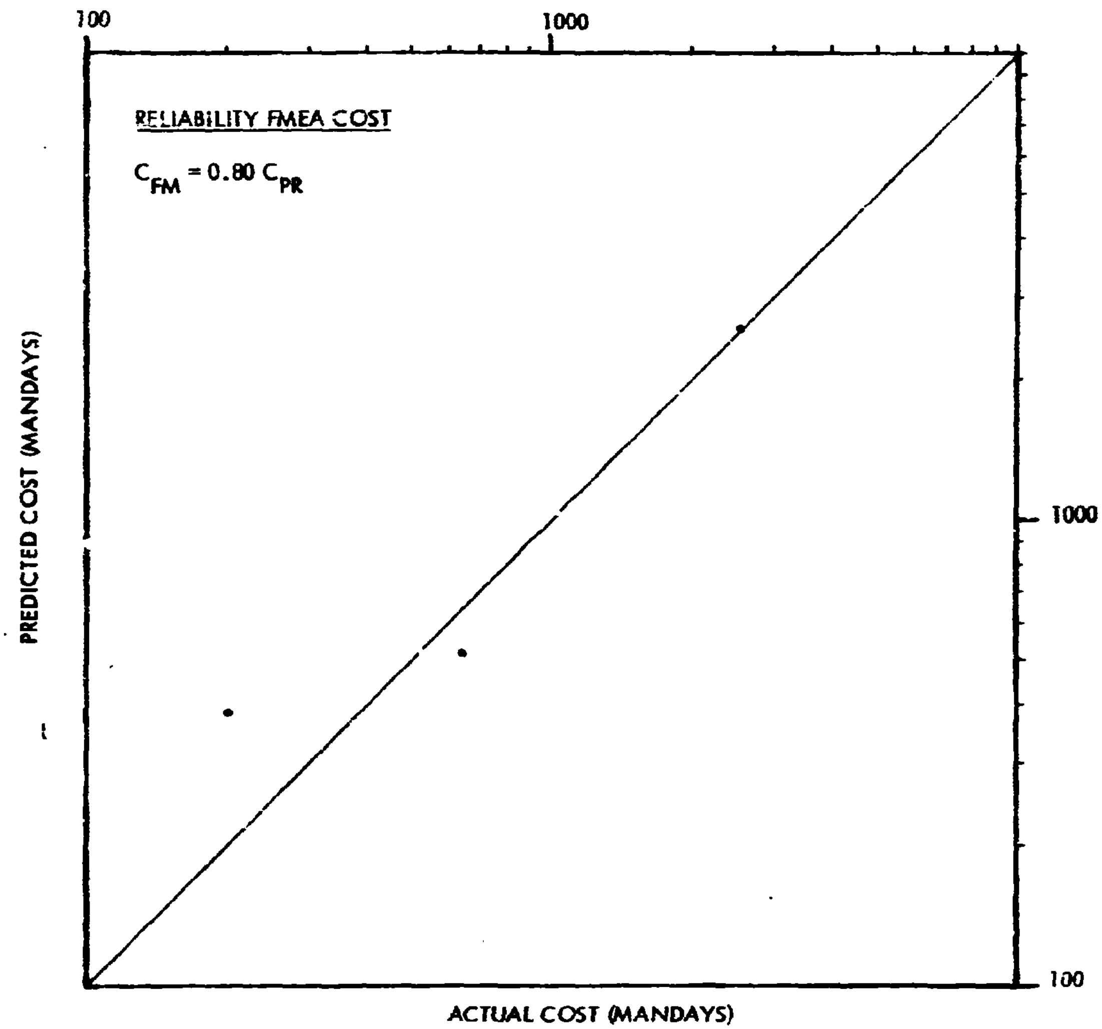


Figure 7. Predicted R FMEA Cost vs Actual R FMEA Cost

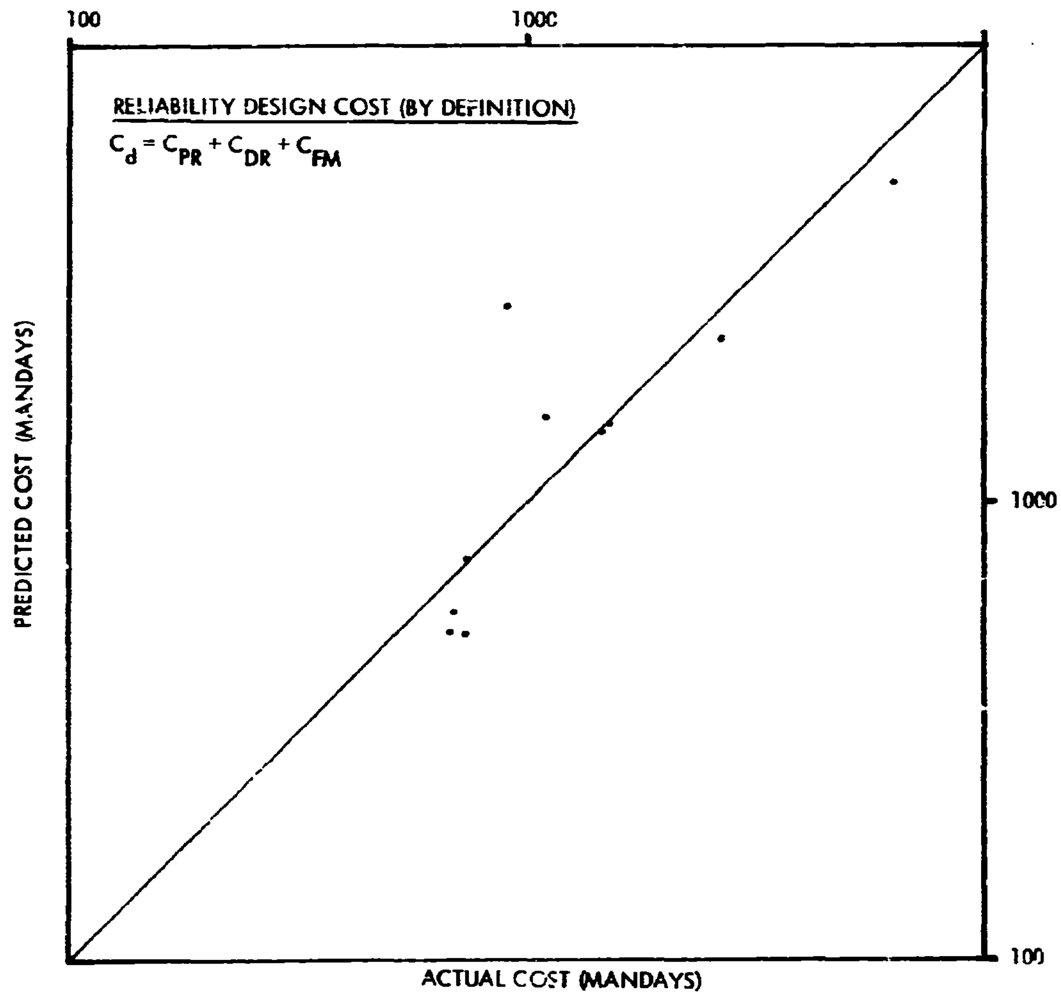


Figure 8. Predicted R Design Cost vs Actual R Design Cost

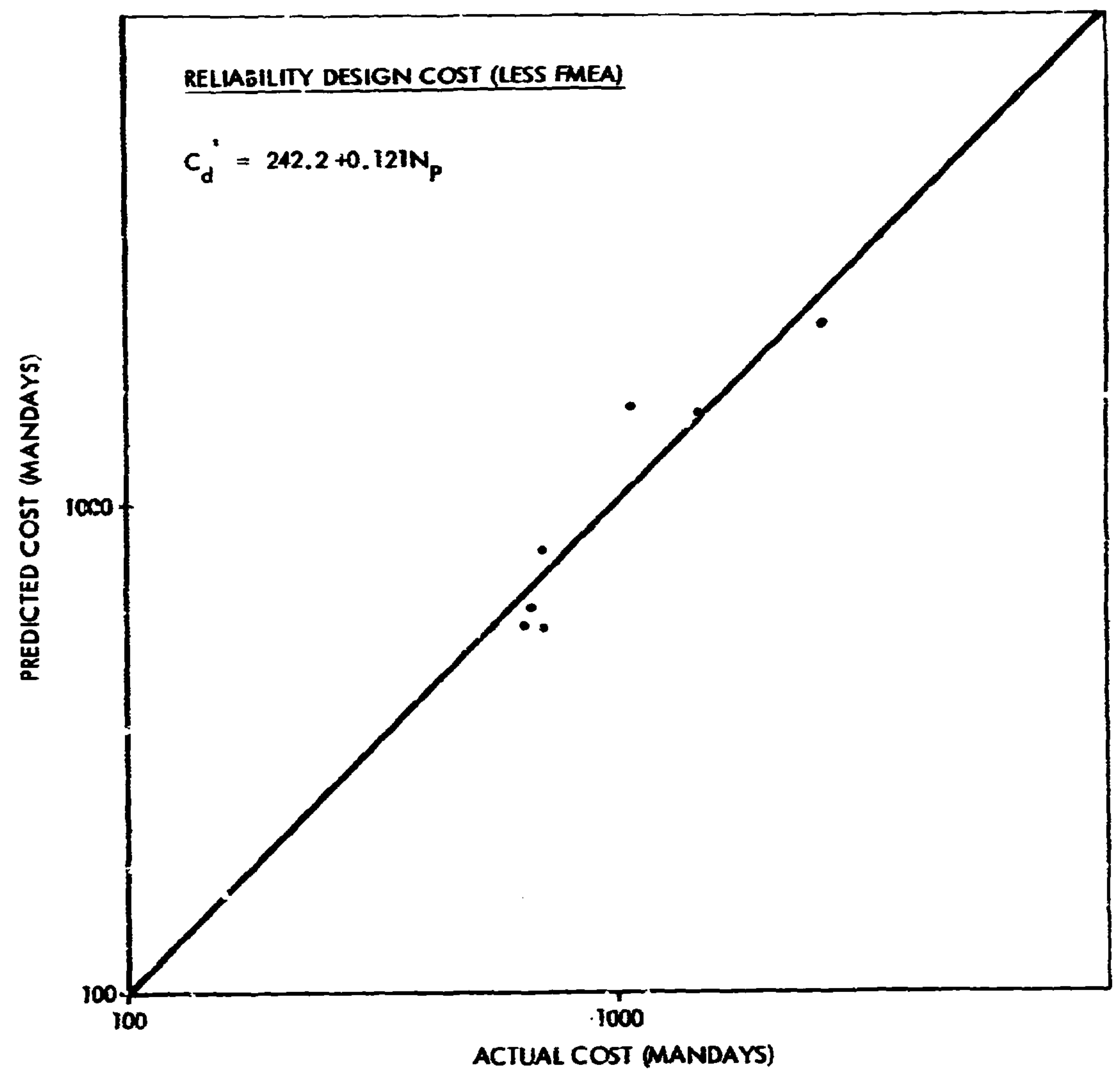


Figure 9. Predicted R Design Cost vs Actual R Design Cost (Less FMEA)

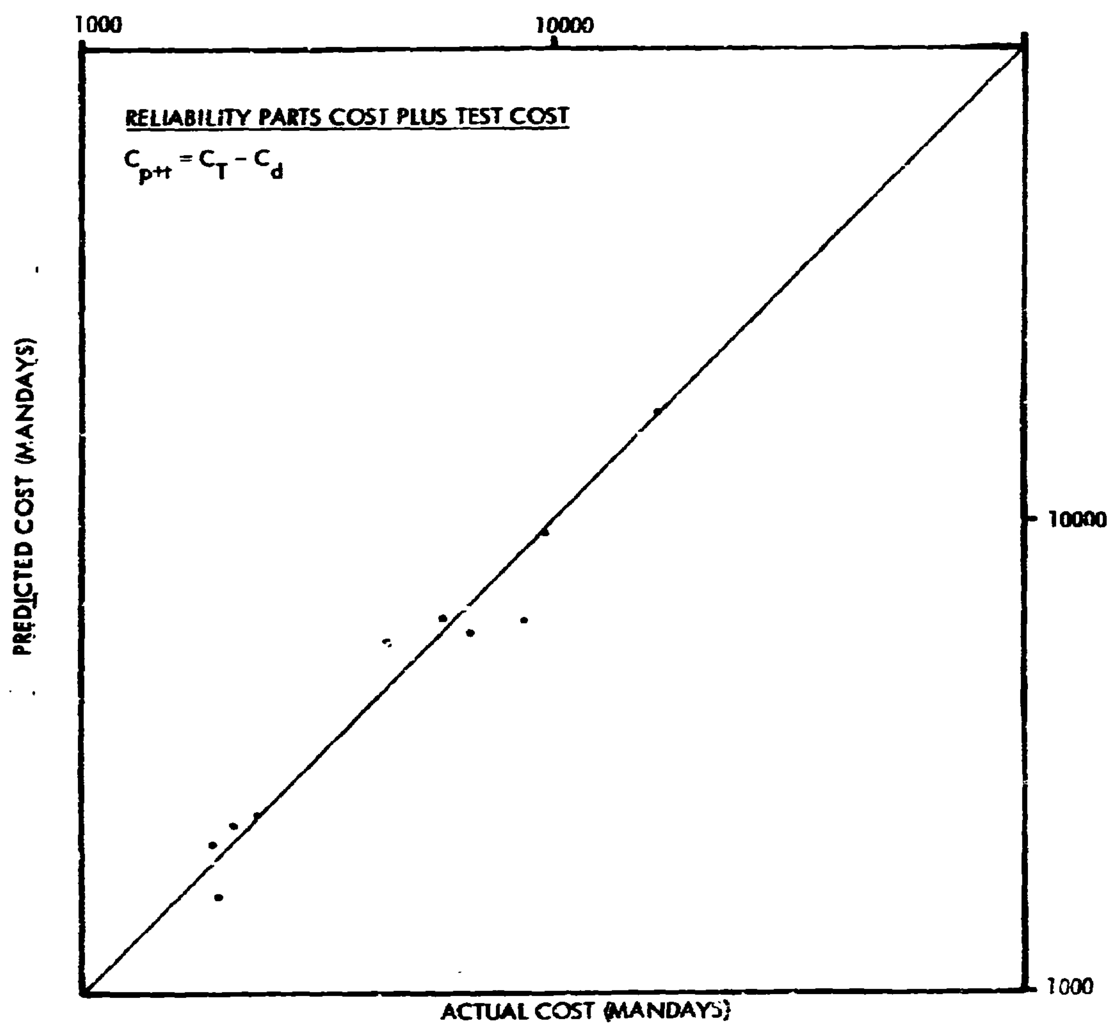


Figure 10. Predicted R Parts Plus Test Cost vs Actual R Parts Plus Test Cost

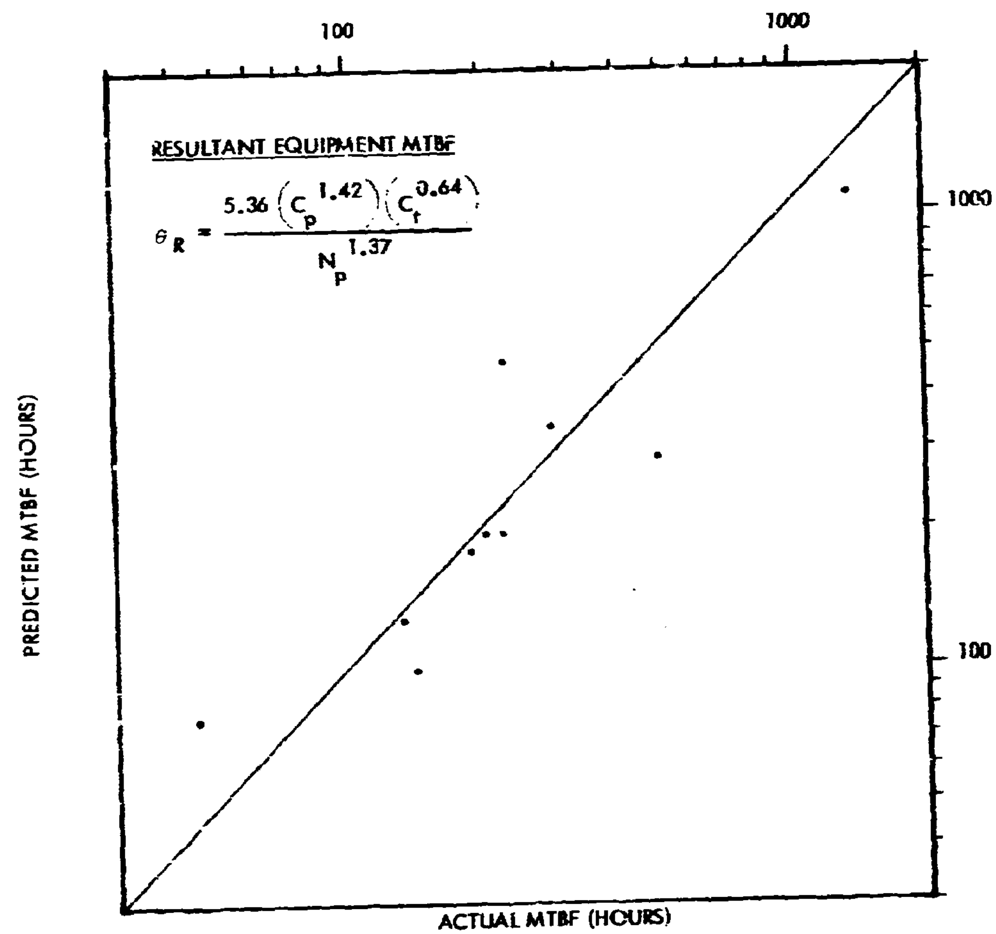


Figure 11. Predicted Resultant Equipment MTBF vs Actual Resultant Equipment MTBF

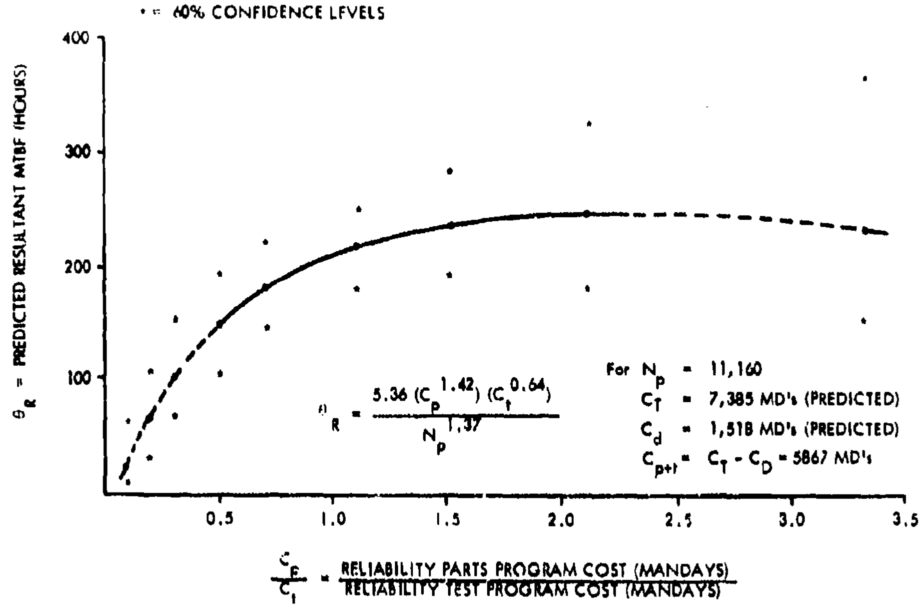


Figure 12. Resultant Equipment MTBF vs Ratio of Parts to Test Cost

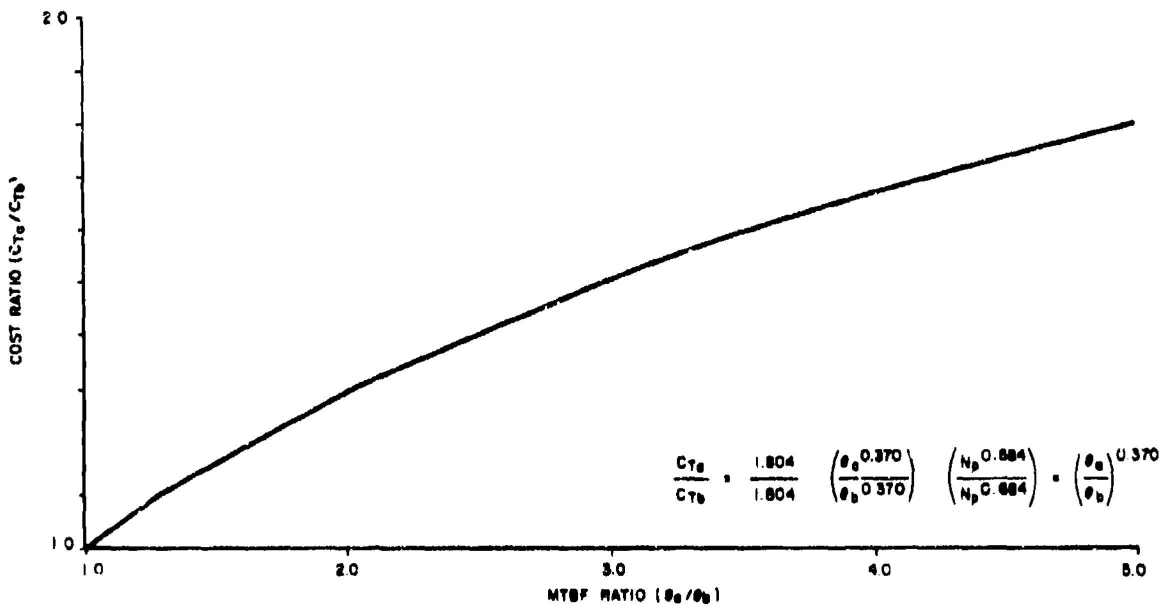


Figure 12a. Cost Ratio vs MTBF Ratio

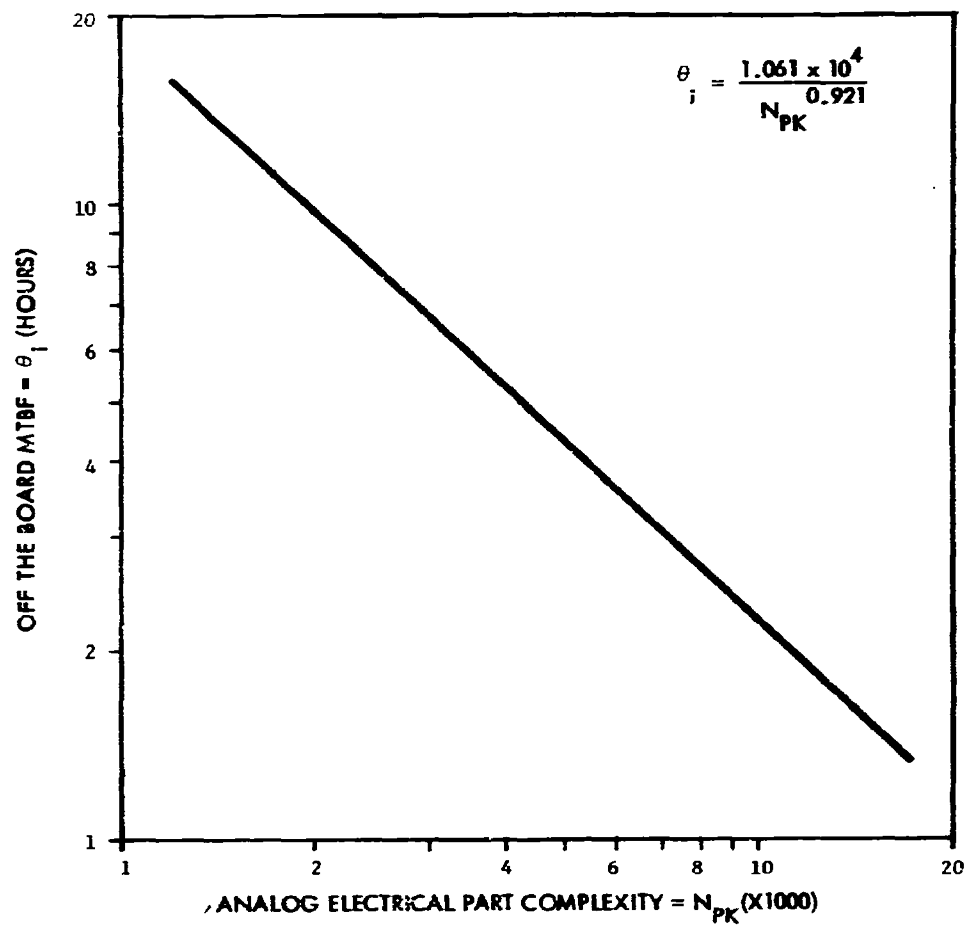
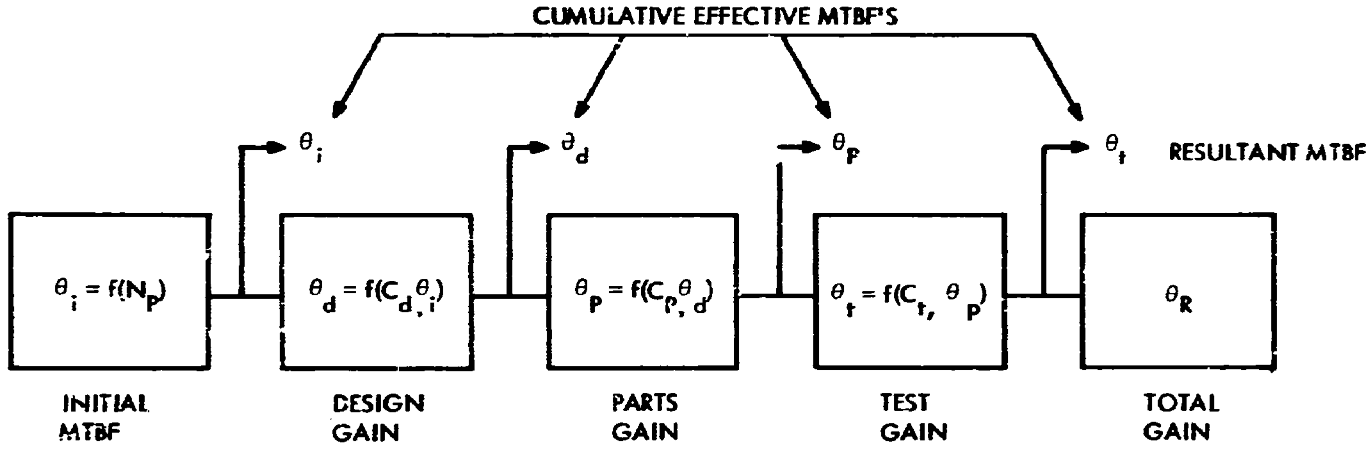


Figure 13. Off-the-Board MTBF vs Equipment Complexity



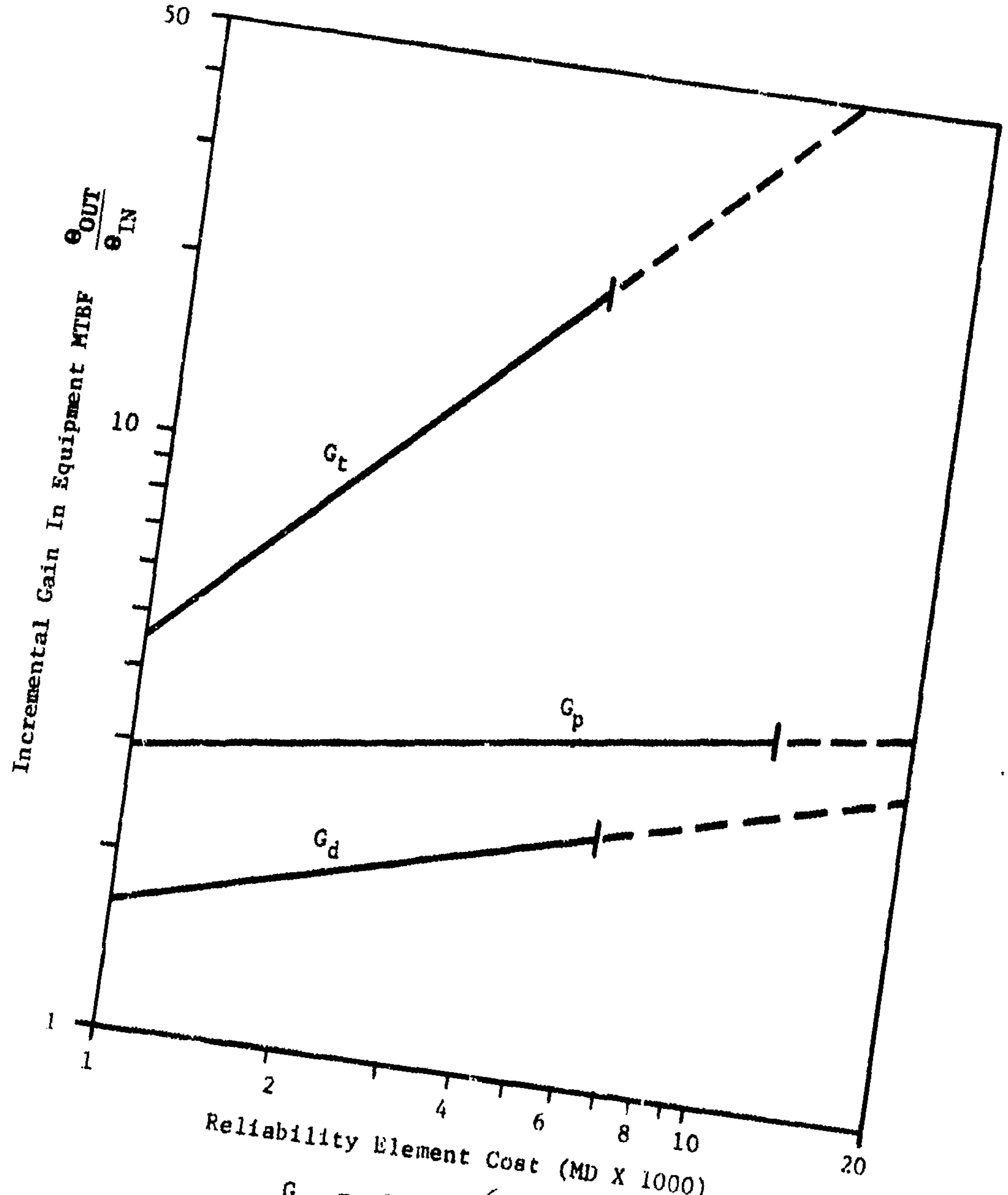
$$G_d = \frac{\theta_d}{\theta_i} = f(C_d) \qquad G_p = \frac{\theta_p}{\theta_d} = f(C_p) \qquad G_t = \frac{\theta_t}{\theta_p} = (C_t) \qquad G_T = G_d \cdot G_p \cdot G_t$$

EFFECTIVE DESIGN MTBF = $\theta_d - \theta_i$

EFFECTIVE PARTS MTBF = $\theta_p - \theta_d$

EFFECTIVE TEST MTBF = $\theta_t - \theta_p$

Figure 14. Incremental Reliability Model



$$G_t = 0.006 \left(C_t^{.952}\right)$$

$$G_p = 1.146 \left(C_p^{.137}\right)$$

$$G_d = 0.302 \left(C_d^{.247}\right)$$

Figure 15. Incremental Gain vs Cost

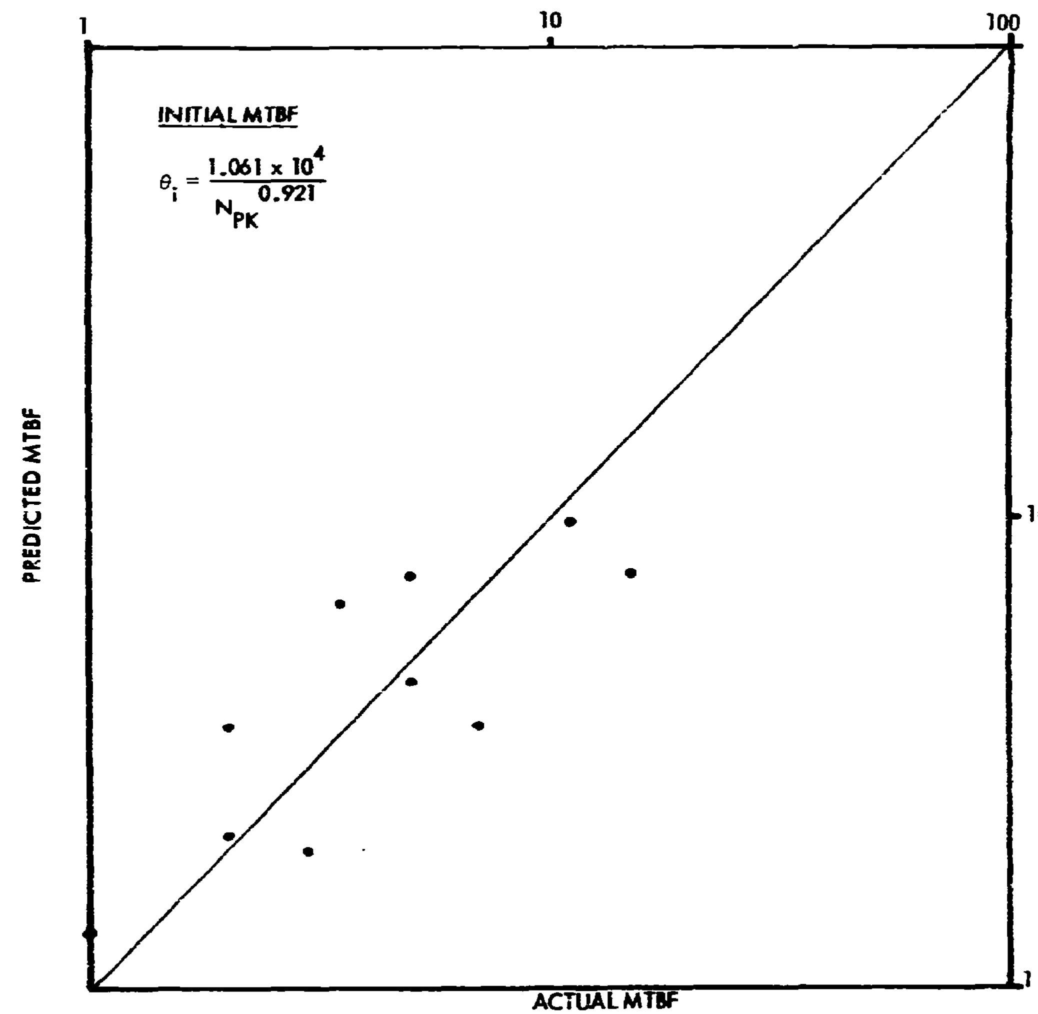


Figure 16. Predicted Off-the-Board MTBF vs Actual Off-the-Board MTBF

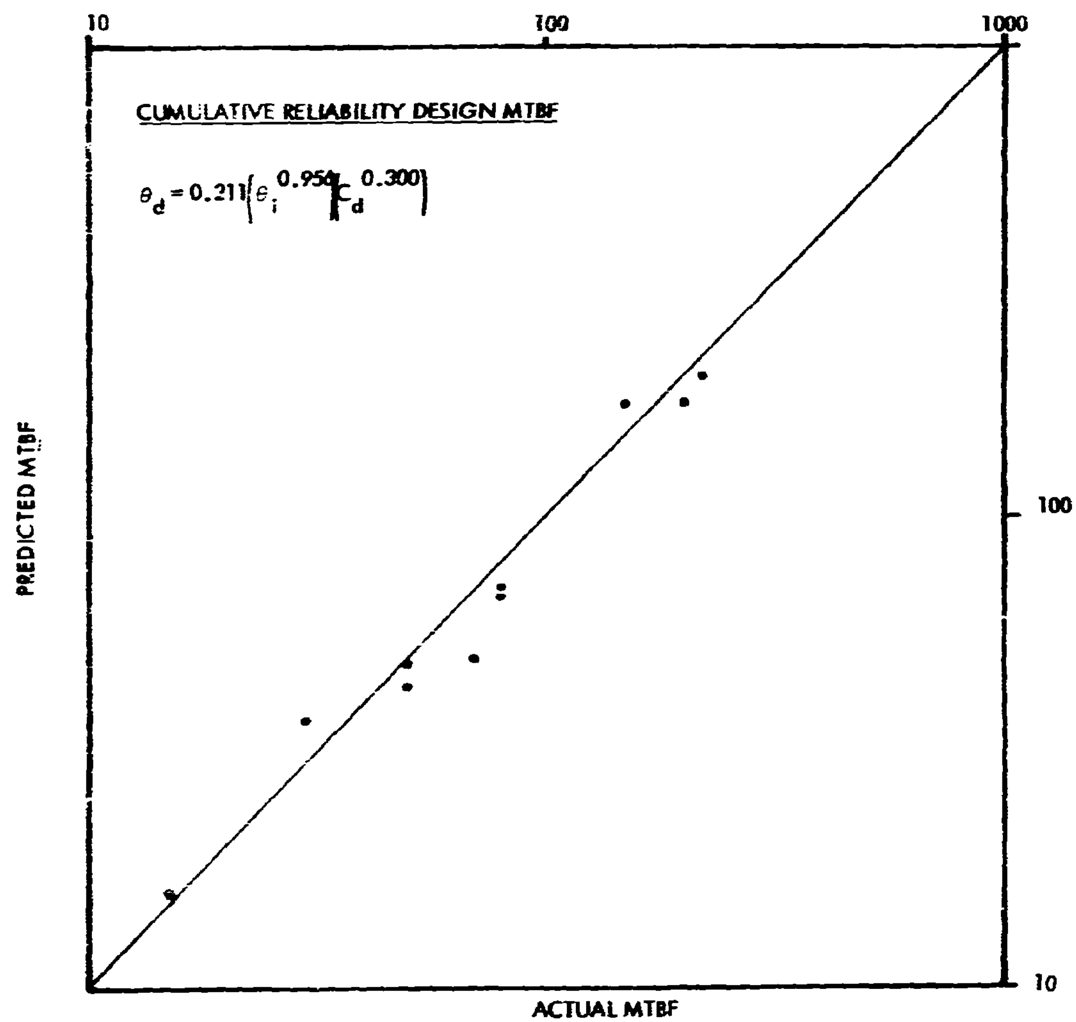


Figure 17. Predicted Cumulative R Design MTBF vs Actual Cumulative R Design MTBF

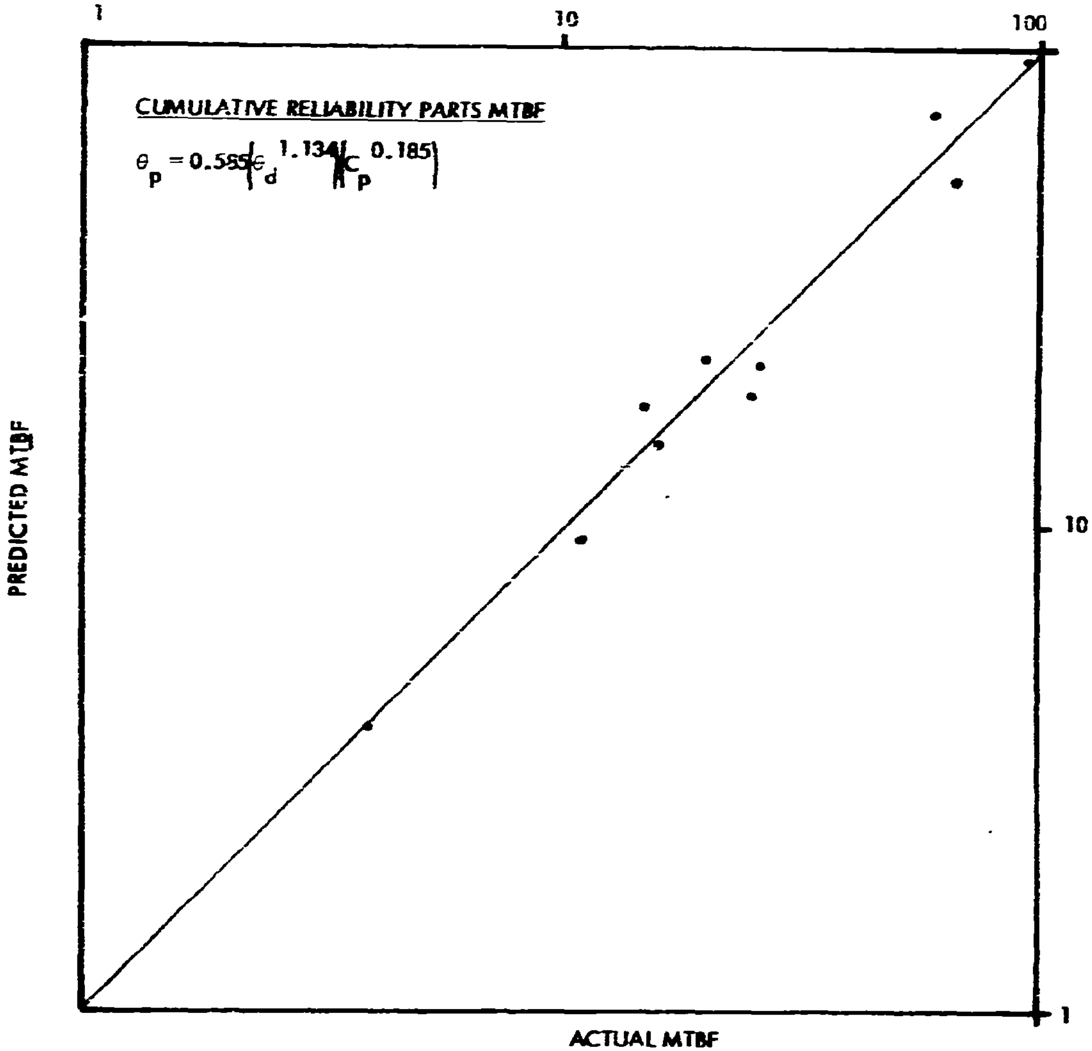


Figure 18. Predicted Cumulative $\underline{R}$ Parts MTBF vs Actual Cumulative $\underline{R}$ Parts MTBF

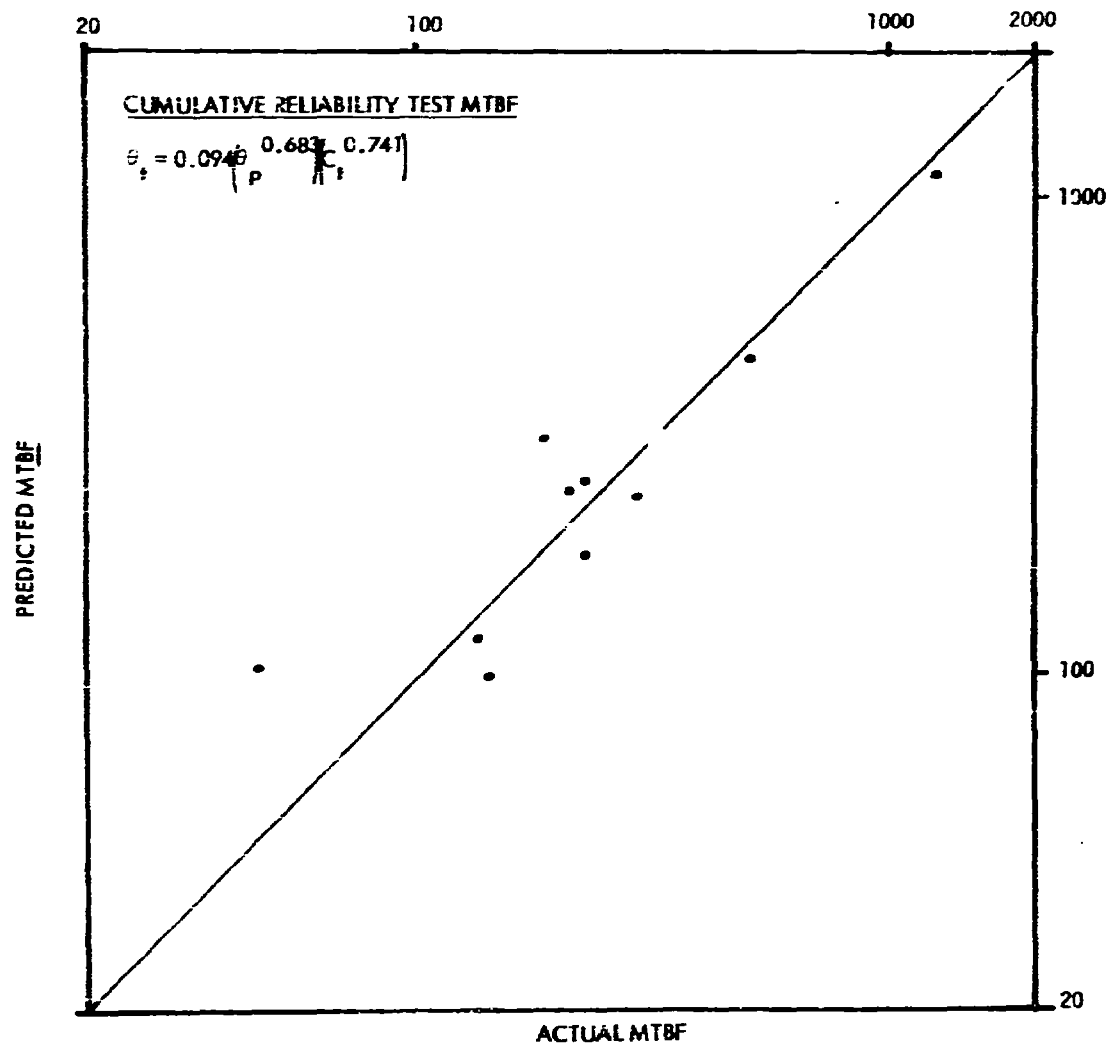


Figure 19. Predicted Cumulative R Test MTBF vs Actual Cumulative R Test MTBF

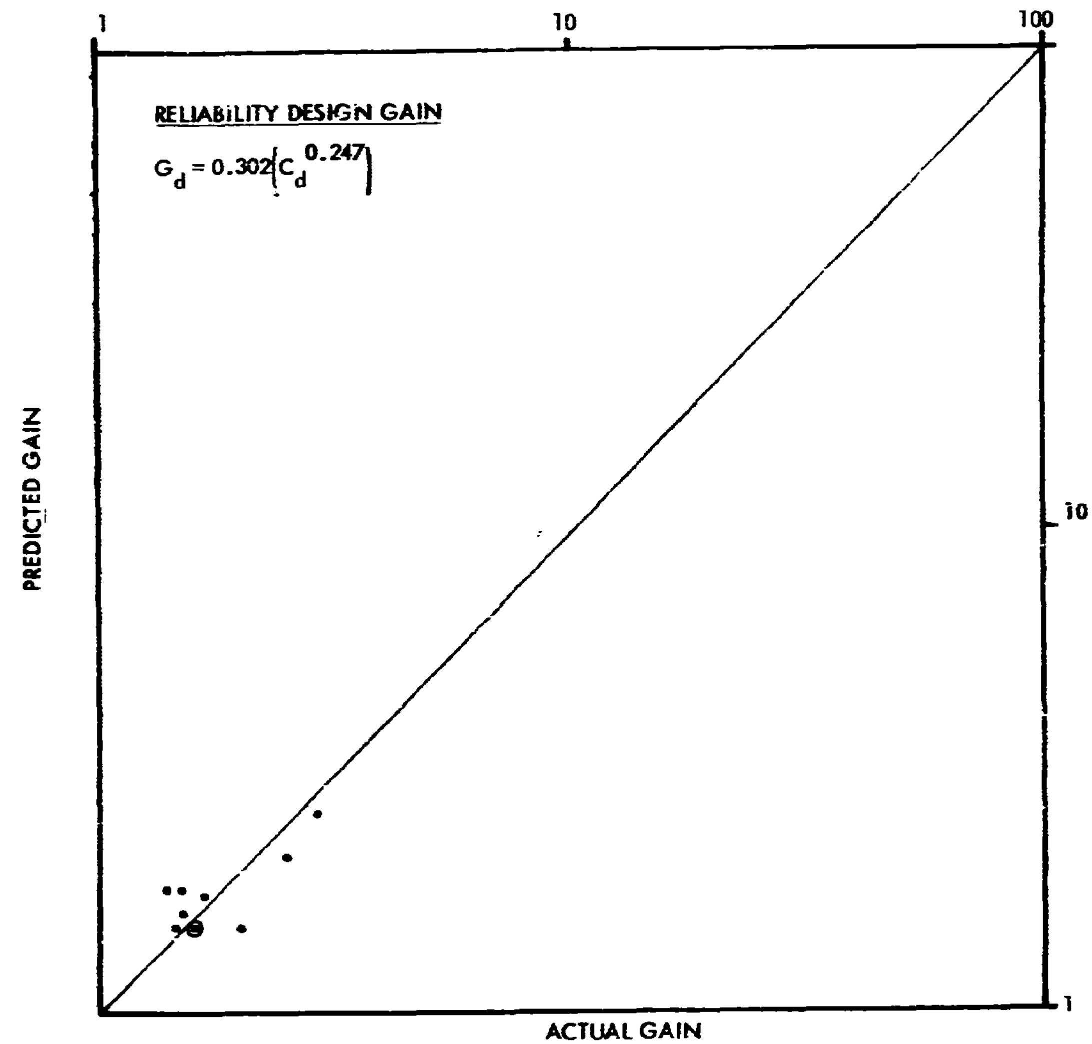


Figure 20. Predicted R Design Gain vs Actual R Design Gain

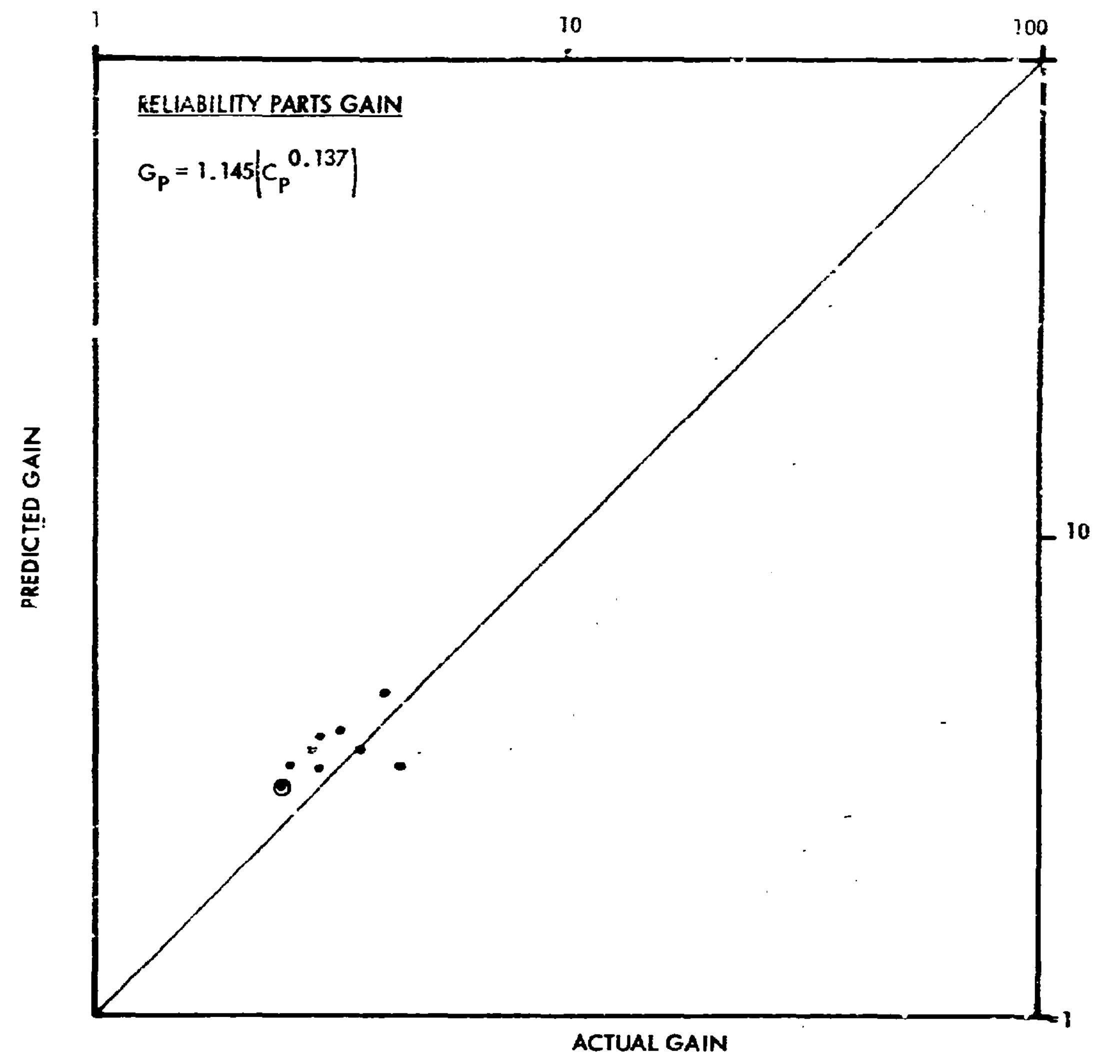


Figure 21. Predicted R Parts Gain vs Actual R Parts Gain

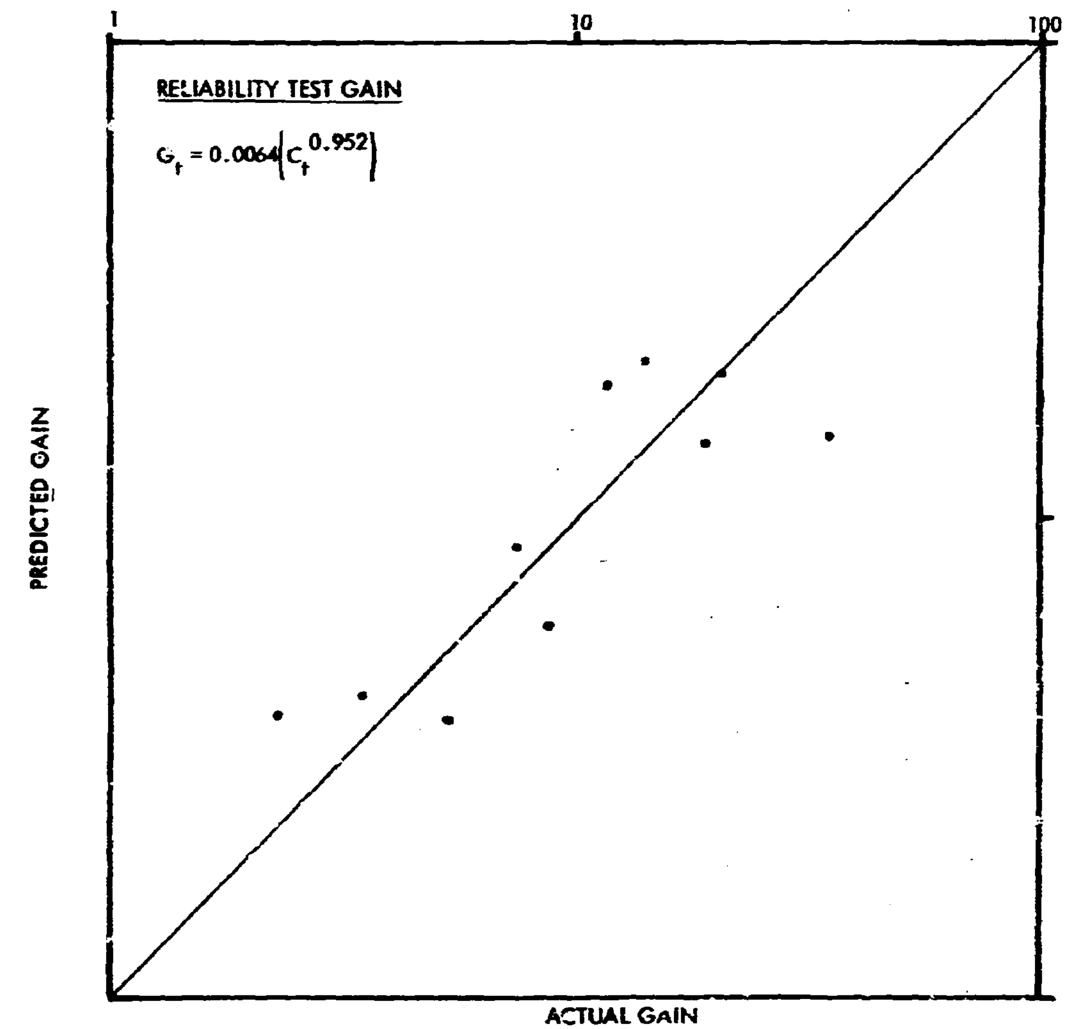


Figure 22. Predicted R Test Gain vs Actual R Test Gain

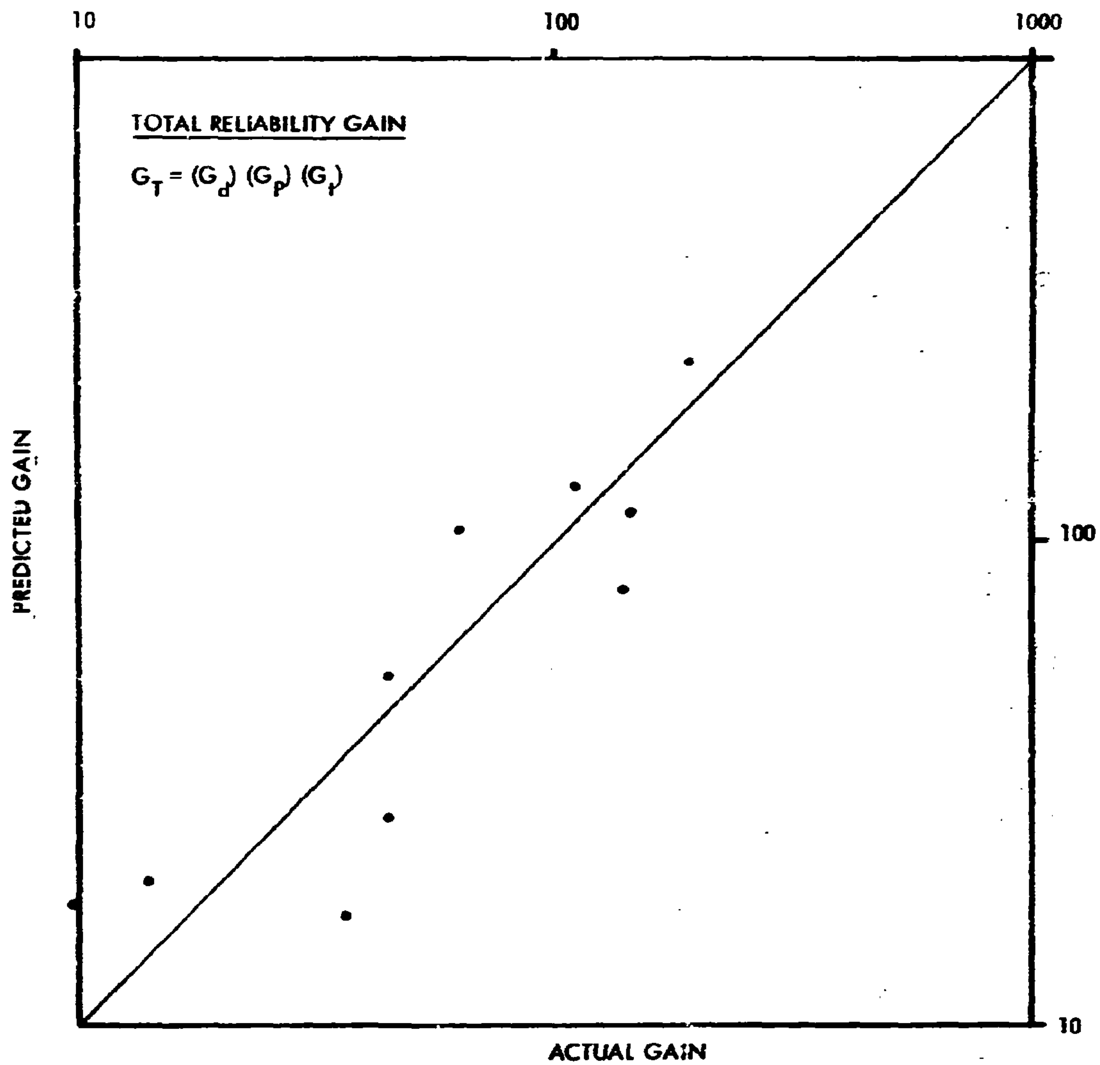


Figure 23. Predicted Total R Gain vs Actual Total R Gain

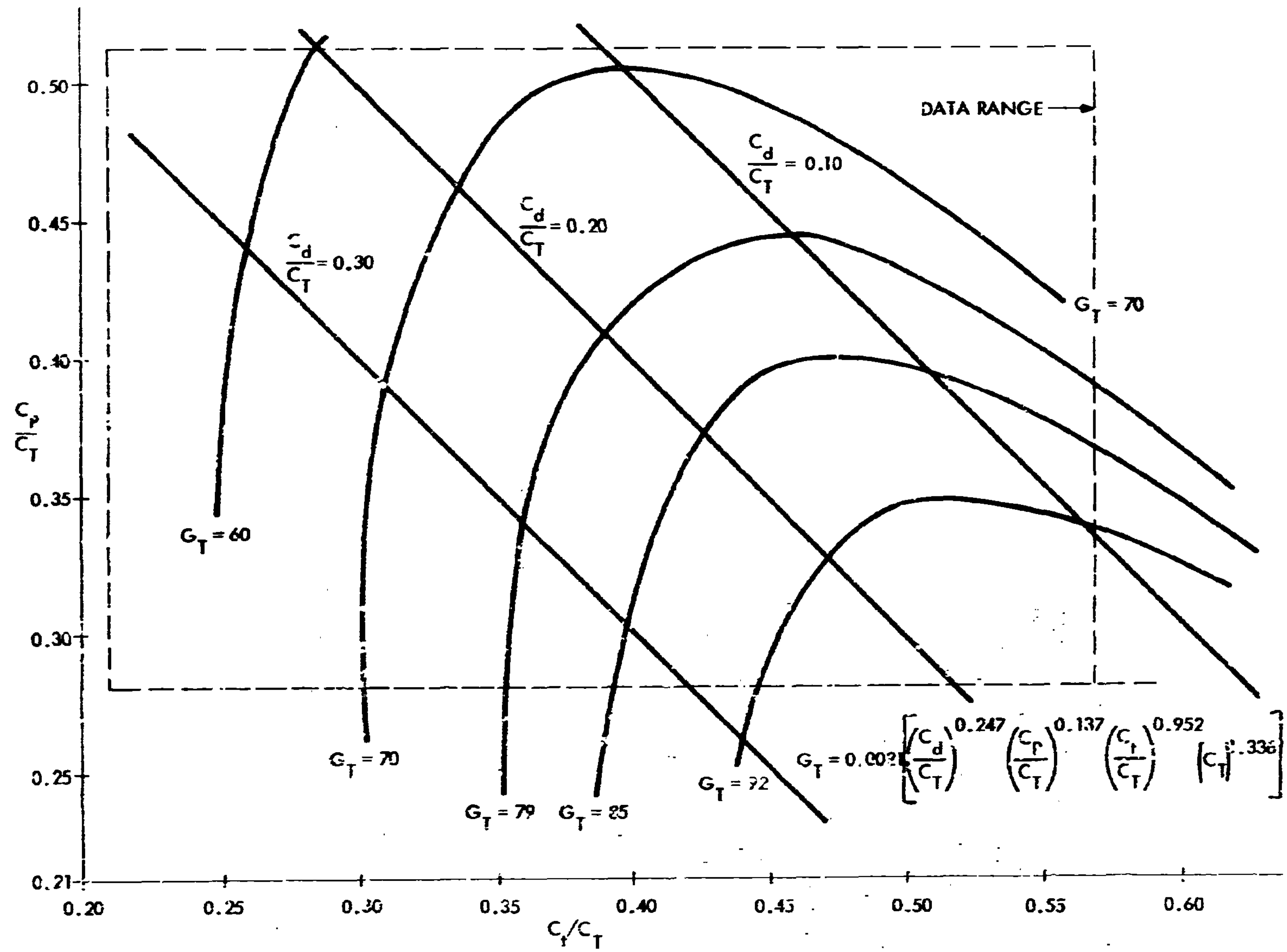


Figure 24. Element Cost Allocation vs Gain

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Significant relationships have been developed for predicting incremental reliability costs, MTBF's and gains in terms of the contractual resultant equipment MTBF requirement and equipment complexity.

The validity of the relationships as applied to a future equipment will depend on the performance requirements, design criteria, and design disciplines of the new equipment being within the bounds of the data base and constraints as defined in this report.

The best measure of accuracy of the prediction relationships is through consideration of statistical confidence as applied to the average of the data. Tables VII and XI of Section IV show the percentage ranges of the actual average values within which the various predicted values will fall for a typical airborne/space equipment with 60, 75 and 95 percent confidence. The conservative 75 percent confidence interval is recommended since the actual data was limited to 10 equipments.

The prediction parameters chosen here seem to account for a significant proportion of the error when predicting incremental reliability costs and MTBF's. Although no proof or disproof of other significant variables was found based on the data of this study, the user of the equations must be aware of the possibility of such variables and consequently apply sound engineering judgment and caution throughout their use.

The relationships developed in this study can be used to predict incremental reliability costs with associated incremental gain as well as to make engineering trade-off decisions with respect to a sound reliability program.

The efforts of this study have shown that cost and reliability are related. It is strongly recommended that the data base be expanded to strengthen and broaden the utility of the relationships. The broadening of the data base should, if possible, include not only more equipments of the same type, but also equipment types other than airborne/space and provide for more data to allow a more detailed analysis of modified and digital designs.

SECTION VI

REFERENCES AND BIBLIOGRAPHY

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APPENDIX A

MUL-REGRESSION COMPUTER PRINTOUT

This appendix contains a typical computer printout of the multiple regression program, MUL-REGRESSION, that was used for the bulk of the regression analyses in the study. This program is part of the time-share statistical program called STATSYST*** developed by the General Electric Company.

```
RUN MUL-REGRESSION (LKRVALC,LMTBF,LQUAPTSB)


VERSION 16 AUG 71 MULTIPLE REGRESSION

INTERCEPT ?YES


INDEPENDENT                                           STANDARD
 VARIABLE     COEFFICIENT          CHECK               ERROR            T-STATISTIC

 LMTBF        3.70162321E-01       3.31E-09          7.42941E-02         4.98239E+00
 LQUAPTSB     6.84466376E-01      -7.50E-08          8.12490E-02         8.42430E+00

INTERCEPT     5.89625701E-01

CODE ?1


    CASE        OBSERVED         PREDICTED
    NO.         VALUE            VALUE            RESIDUAL          % DEVIATION

     1         1.00626E+01      9.98369E+00      -7.89061E-02          -0.79
     2         9.38824E+00      9.36535E+00      -2.28814E-02          -0.24
     3         8.82114E+00      9.11258E+00       2.91435E-01           3.20
     4         9.23640E+00      8.94520E+00      -2.91202E-01          -3.26
     5         8.67989E+00      8.86896E+00       1.89071E-01           2.13
     6         8.95144E+00      8.90725E+00      -4.41918E-02          -0.50
     7         7.99834E+00      7.98498E+00      -1.33590E-02          -0.17
     8         7.93559E+00      7.94745E+00       1.18656E-02           0.15
     9         7.83676E+00      7.89170E+00       5.49358E-02           0.70
    10         7.88043E+00      7.7836[illegible]E+00      -9.67677E-02          -1.24

                            SUM OF RESIDUALS =     -6.55651E-07

               STANDARD ERROR OF THE ESTIMATE =     1.80033E-01
```

CØDE 72

ANALYSIS ØF VARIANCE

SOURCE	DF	SS	MS
REGRESSION	2	4.95862E+00	2.47931E+00
ERRØR	7	2.26884E-01	3.24120E-02
TOTAL	9	5.18551E+00	

F-RATIO = 7.64936E+01, A 100.00 % VALUE

MULTIPLE REGRESSION CØEFF. = 0.977878556

CØDE 74

CØVARIANCE MATRIX

(LMTBF)	7.737E-01	2.800E-01	4.780E-01
(LQUAPTSB)	2.800E-01	6.469E-01	5.464E-01
(LKRVALC)	4.780E-01	5.464E-01	5.762E-01

VARIABLE	MEAN	STANDARD DEVIATIØN
(LMTBF)	5.41627E+00	8.79584E-01
(LQUAPTSB)	8.88949E+00	8.04291E-01
(LKRVALC)	8.67908E+00	7.59057E-01

CØDE 75

CØRRELATIØN MATRIX

(LMTBF)	1.0000000	0.3958072	0.7159998
(LQUAPTSB)	0.3958072	1.0000000	0.8950321
(LKRVALC)	0.7159998	0.8950321	1.0000000

```
CODE ?7

          CONFIDENCE BANDS AND PREDICTION INTERVALS FOR E(Y)

 2 DATA VALUE(S), NO. OF CONFIDENCE LEVELS, & LEVELS -- ?5.41627,8.88949
?3,.95,.75,.60

CONFIDENCE BANDS ?YES


          CONFIDENCE BANDS FOR E(Y)

CONFIDENCE    LOWER          PREDICTED        UPPER            BAND
  LEVEL       BOUND            VALUE          BOUND            WIDTH


  95.00    8.54446E+00     8.67908E+00     8.81370E+00     2.69244E-01
  75.00    8.60767E+00     8.67908E+00     8.75049E+00     1.42816E-01
  60.00    8.62807E+00     8.67908E+00     8.73009E+00     1.02026E-01

PREDICTION INTERVALS ?NO


CODE ?0

STORE PREDICTED VALUES IN STATSYSTEM ?NO


READY
?STOP
```

APPENDIX B

RELIABILITY PLANNING AND MANAGEMENT (RPM) METHODOLOGY

This appendix, a reprint of Reference 5, presents a new approach to the reliability planning and management of complex weapon systems. This methodology was developed and is being used by the Aerospace Electronic Systems Department of the General Electric Company.

RELIABILITY PLANNING AND MANAGEMENT - RPM

J.D. Selby, General Manager
and
S.G. Miller, Manager-Reliability and Quality Assurance

General Electric Company
Aerospace Electronic Systems
Utica, New York

INTRODUCTION

This paper presents a new approach to the reliability planning and management of complex weapon systems. To set the stage, it is necessary that certain basic assumptions be accepted. First, it must be assumed that for any new weapon system a realistic reliability model has been developed. Secondly, it must be assumed that the model reflects a reasonable apportionment of the reliability mean time between failure (MTBF) requirements among the various subsystems or equipments. In other words, we assume that when a request for proposal (RFP) is released for bid, it contains a reliability requirement that can be met.

STATEMENT OF THE PROBLEM

The problem I will address is the credibility in avionics reliability planning and acquisition management. Experience has demonstrated that to a varying degree, a reliability program credibility gap exists between stated equipment reliability requirements and realized or realizable achievement. This gap stems largely from the lack of a uniform method of reliability program structuring and evaluation. The result is implementation of unrealistic programs with unachievable requirements. These shortcomings become evidenced in a lack of understanding between the buyer and contractor as to reliability requirements, risks, and program impact to be associated with a given equipment development plan.

Typically, each equipment proposal describes an overview reliability program apparently compliant with specification requirements. In a detailed examination of individual implementation plans, the content may vary widely, thus opening to question program credibility and achievable reliability. This credibility gap is first evident in the dimensioned equipment, resources, facilities, effort, time, and their planned utilization, projected by contractors as required for compliant program execution. Currently, both the contractor proposal manager and the equipment buyer lack tools with which to evaluate with reasonable conviction which, if any, of the proposed programs can result in a product compliant with the reliability requirements.

Evidence as to the degree of reliability nonconformance currently being experienced is shown by a review of the field performance (Table I) of a 1968/1969 vintage aircraft weapons system. This system, comprised of new and modified hardware procured under a program utilizing MIL-STD-785, is augmented by specific requirements for reliability qualification testing, reliability product screening, production FACI, and production reliability acceptance testing. A within-program review of individual product reliability performance, during the first quarter of 1970, indicates that the equipment's achieved mean time versus contract specified was noncompliant by a factor as large as 20:1, typically 10:1, with only a few select products being compliant. In addition, reliability performance compliance would not appear to be tied directly to a specific contractor or the equipment mean time goal, since complex and simple equipments are both compliant as well as significantly noncompliant. Again, these results were experienced in an environment where the equipments were procured to dimensioned reliability requirements in the late 60s.

TABLE I. WEAPONS SYSTEM FIELD RELIABILITY COMPARISON*

SUBSYSTEM	MTBF GOAL	FLIGHT MTBF (HRS) JAN-MAR 1970	% MTBF ACHIEVEMENT
LOGIC UNITS	800	849	100
TAPE TRANSPORT	500	36[illegible]	70
DISPLAY C	1000	915	90
INDICATOR	333	203	60
SEARCH RADAR	150	39	20
COMPUTER	1500	183	10
UHF COMMUNICATIONS SET	1200	118	10
FLIGHT DIR COMPUTER	1000	80	10
HF COMMUNICATIONS SET	1200	92	10
INERTIAL NAVIGATION	750	57	10
DISPLAY A	1000	87	10
DISPLAY B	2000	108	5
NAVIGATION-ALTITUDE RADAR	1000	54	5

AIRCRAFT WEAPONS SYSTEM 1968/1969 VINTAGE

- R PROGRAM PER MIL STD-785
- R DEMONSTRATION
- R ACCEPTANCE
- FACI

Having established that realized product reliability is widely diverse and typically low, it is

necessary to identify the cause to facilitate corrective action and establish a method for evaluating and appraising program reliability potential, prior to and during the contract acquisition process. Insight into the cause and impact of the lack of reliability achievement may be gained (Figure 1) from a review of the time-phased performance of the avionic suppliers on a completely separate weapon system development of the mid-60s.

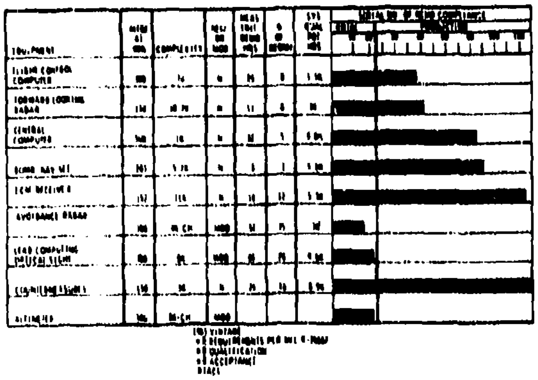


Figure 1. A Weapons System Avionic Suppliers' Performance

A number of observations become clear from this historical data:

1) The original weapons system reliability apportionments were realistic as evidenced by their eventual achievement

2) Timely R&D compliant performance was not achieved

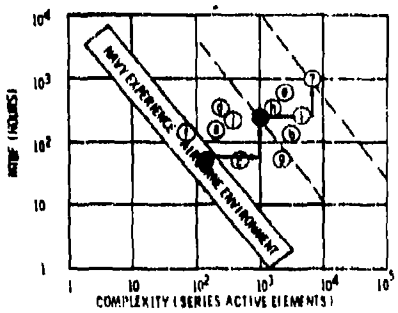
3) Reliability nonconforming production hardware was delivered

4) Modified equipments with their attendant reduced development risks achieved compliance in a more orderly and timely fashion than newly developed equipments.

For the newly developed equipments, the initial average achieved reliability was approximately 8% of their specified requirement. Each equipment required extensive test evaluation and improvement prior to achieving compliance. The lack of compliance was equally applicable to a cross section of contractors and product types with complexity variation of 17:1. These results are typical of weapon systems designed with the modern technology, methods, and automation of the 60s. A way of stating the problem in its totality is that management, government and industry, lack a quantitative yardstick with which to dimension, plan, manage, fund, and monitor reliability development as a part of equipment development.

THE NEED FOR A SOLUTION

The trend in product reliability requirements from the 1950s through the 1960s can be portrayed (Figure 2) by the reliability plot from MIL-STD-756A as updated and augmented by GE/AES's avionics product data base from the 60s. This plot relates systems mean time between failure to system complexity as determined by the Navy from airborne avionics experience through the early 1960s.



	PROGRAM	MTBF (HR) OR % SUCCESS		EQUIPMENTS	
		REQ'D	DEMO	SHIPPED	THRU ENVIR TEST
a	RAPID TUNE	200	277	848	848
b	AN/APQ-113	137	202	341	341
b	AN/APQ-114	137	812	105	105
c	AN/ALQ-87	50	56	1000	1000
d	AN/AXR-13	500	655	40	26
e	AN/AYA-8 (LU)	800	1200	55	52
f	MISSILE	150	618	1940	78
g	EXX RADAR	77	NEW	-	-
h	EXX RDP	500	NEW	-	-
b	AN/APQ-144	137	-	-	
i	F-111 FLT CONT	310	375	510	510
j	AN/ASQ-23	450	1578	112	112

Figure 2. Product Requirements and Experience - The 1950s and 1960s

The GE/AES data also encompasses airborne equipments of a conventional nonredundant design, reflecting nearly 100K hours of equipment level testing on a diverse complement of products developed and volume produced to reliability requirements for a number of government and industrial customers throughout the decade. Evident from this chart is a trend indicating that through the decade the reliability requirements and product complexity have, on the average, each increased by a factor of 10.

Projecting forward to the requirements and product needs of the technically sophisticated 70s, it appears reasonable to expect a continuing extension of this reliability trend, resulting in an

additional one order of magnitude increase in requirements paralleling the growth of the 1960s. While it is not clear today exactly the form this extension will take in the 1970s, it is clear that either more complex equipments with today's mean times or equipments centering at the current high end of the complexity scale with more timely achieved reliability will be required. Recognizing the difficulty and obvious lack of uniform success experienced in coping with the reliability requirements of the 1960s, and currently projecting increasing requirements for the 1970s, it is clear that a change in the practices of Reliability Planning and Management is mandatory. To meet this need, a methodology is required which has the credibility of an exacting science, incorporates the flexibility for alternative program planning, and contains standardization factors to facilitate a uniform evaluation structure suitable for application by both contractor and buyer.

DEPARTURE FROM THE CLASSIC SCHEME

The classic method of reliability projection is prediction. From a planning viewpoint, this typically consists of a preliminary "before design" and a refined "during design" estimate of the product's analytical mean time. Classically and erroneously, buyer and seller alike assume that this analytical prediction is representative of the expected performance of the product as initially manufactured. This is not the case in the design and manufacture of avionics products. Many unknowns and intangibles do exist that cannot be analytically forecast, foreseen, or controlled. Living in this environment, it then becomes clear that extended product experience and familiarity in the intended use environment is necessary to identify a whole family of hidden defects for corrective action, and corrective action test validation. The crux of the reliability planning problem is the lack of ability to dimension for a new product the extent of the evaluation test need. This evaluation may be extensive enough to affect total program assets, resources, time, and facilities. Historically, provisions for this need are not dimensioned and provided. This is not the case at GE/AES where consideration is given to the interrelated program requirements through the use of Reliability Planning and Management (RPM).

RPM CONCEPT

To cope with the reliability planning problem of bridging the gap between stated reliability mean time numbers and the reality of program structuring required to effect a product that is technically and timely compliant, we have developed a methodology called Reliability Planning and Management (RPM). This concept reduces the planning and resource allocation requirements into a simple quantized objectively usable format.

Figure 3 portrays the basic criteria, constraints, and factors which must be met when structuring a reliability program compliant with the concept. To apply this methodology, it is first mandatory that no laws of physics are violated by the designer and that beyond-the-state-of-the-art requirements are not imposed. Operating within this framework, the criteria to be fulfilled consist of prediction versus requirement, initial product capability assessment, reliability growth rate, product experience gained through extended environmental exposure, calendar time, and change constraints. Successful program implementation requires that specific compliance be achieved for each criterion as follows.

<u>Prediction versus Requirement</u> specifies that prior to release, the design be simplified and parts stress and screening levels be adjusted until an analytical reliability prediction based on technically established and credible failure rates (use MIL Handbook 217A) will yield at a minimum a prediction 125% of the requirement

<u>Product Capability</u> requires that a realistic appraisal be made of the new or changed design, recognizing the inevitability of flaws which constrain initial performance to 10% of the inherent analytical capability.

<u>Reliability Rate of Growth</u> projects that reliability improvement for complex equipment when operating in their intended use environment is approximately inversely proportional

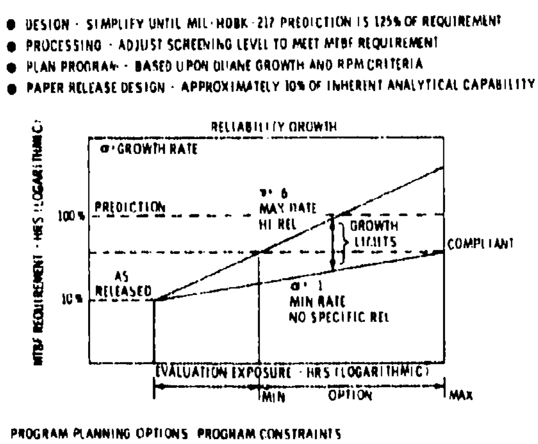


Figure 3. Reliability Planning

to the square root of the cumulative operating (test) time, and that for a constant level of corrective action effort and timely implementation, reliability growth closely approximates a straight line in log-log scales as initially postulated in a reliability growth model in 1962 by J.T. Duane. Limits of reliability rate of growth for avionics have been empirically derived by GE/AES from the cumulative data of J.T. Duane and GE/AES. Growth limits are estimated as a maximum rate of approximately .6, which we have not achieved, an established and experienced rate of .5 for a hard-hitting aggressive reliability program with management support spanning all functions of a knowledgable organization. A minimum rate of .1 can be expected on those programs where no real specific consideration is given to or for reliability. In this latter case, growth is largely due to the need to effect solution for the clearly obvious problem impacting production and from corrective action taken as a result of user experience.

Product Evaluation Exposure structures the test evaluation time required to effect a compliant product, based on a specific, initial capability, growth rate, and requirement. With the exposure hours established and a valid assumption on achievable test efficiency (we use 200 equipment exposure hours per calendar month for new complex avionics), then the *tradeoffs* in program planning can be objectively made by contractor and buyer, encompassing the acceptability of the initial design, its design margin, number of equipments to be placed on test, facilities, test time, calendar time, and ultimately program cost.

Origin of Reliability Growth

The basic concept of a patterned reliability growth is the basis for the evaluation portion of the RPM model, first recognized and published by J.T. Duane of GE Company's Motor and Generator Department in 1962. His analysis of test and operational data for programs with test times as high as 6 million hours on five divergent groups of products (two hydro-mechanical devices, two complex aircraft generators, and a jet engine) formulated a pattern which resulted in the following concept (see Figure 4):

> Reliability improvement of complex equipment follows a mathematically predictable pattern.
>
> Reliability improvement is approximately inversely proportional to the square root of cumulative operating (test) time.

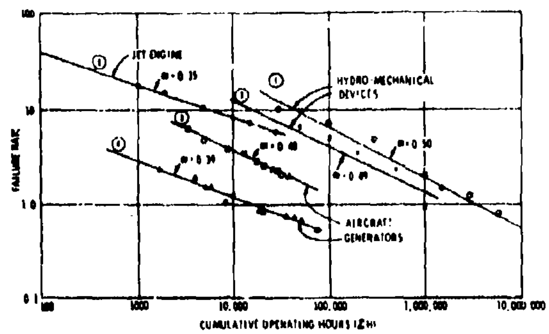


Figure 4. Original Duane Data

> For a constant level of corrective action effort and implementation, reliability growth closely approximates a straight line on a log scale.

This pattern has been confirmed to be applicable to avionics equipment by GE/AES from data on four separate programs.

Experience Performance and Model Confirmation

The development of the RPM model occurred as an outgrowth of studies aimed at deriving a meaningful reliability development program projection model from actual development experience. Two of several GE/AES programs have been selected and analyzed in this paper for the purpose of illustrating model conformance. In evaluating achieved performance versus that which could have been predicted to occur, it will be shown that excellent correlation with the Duane growth forecast and the higher order RPM model does exist.

The first selected program, Figure 5, conducted between 1961 and 1965, called for an equipment development as part of an airborne fire control system modernization. From the history of this program, it is observed that the new equipment initially performed at approximately 10% of the predicted MTBF and achieved a reliability growth rate (α) of .5 during a comprehensive reliability program over an extended period of evaluation test with product change flexibility. Conversely, significant reliability growth did not continue during production under disciplined change constraints. The reliability requirement achieved and demonstrated during development was shown to persist in production across 209 equipments for 25,360 test hours.

The second program, Figure 6, a complex radar equipment, five times as complex as the first program and a vintage of the middle 60s,

had essentially the same attributes as the first program. Excellent model correlation was again shown by initially performing at 10% of the predicted MTBF, experiencing a growth rate of .5, under a comprehensive reliability improvement program and slow growth under production constraints.

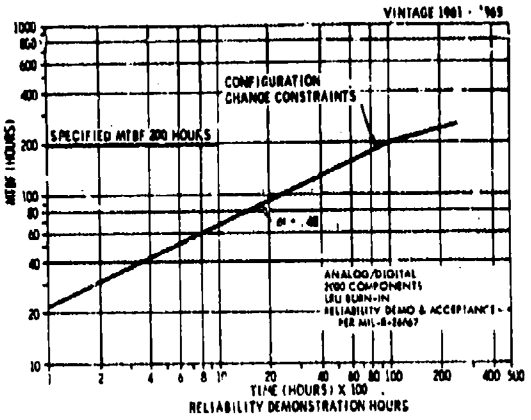


Figure 5. RPM Model - Program 1

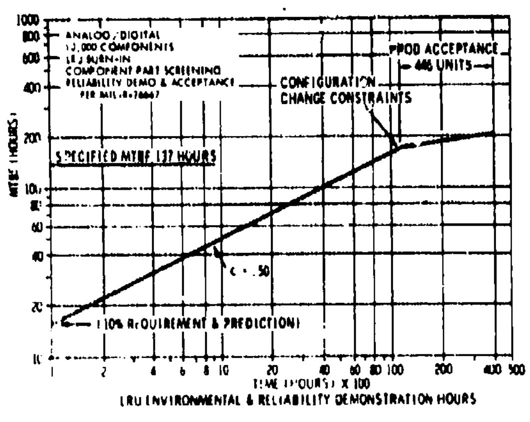


Figure 6. RPM Model - Program 2

Correlation with the RPM model in these two examples was accomplished after development was completed, and not through a priori program planning as presented in this paper. In each case, reliability improvement occurred as a result of intensive, well-directed recovery programs implemented at the expense of program interruptions and delays. The second program, in mid-course, applied the Duane growth concept as a progress monitoring tool, contributing significantly in insight to the formulation of the RPM model. The model, now recognized, confirmed, and dimensioned, was first contractually applied in forward fit to an equipment development aimed at alternate and expanded capabilities for a currently new equipment. The task involved a 20% design change to an 11K part system where the first production lot was required to demonstrate reliability performance equal to that specified for the unmodified equipment.

The third program, Figure 7, displays the RPM plan and development experience resulting in an equipment completely compliant in first-lot production demonstration. You may note that this program plan reflected a certain lack of confidence in that a conservative α of .375 was utilized. Subsequent to the successful utilization of the model, two additional equipment developments have been undertaken, utilizing an α of .5.

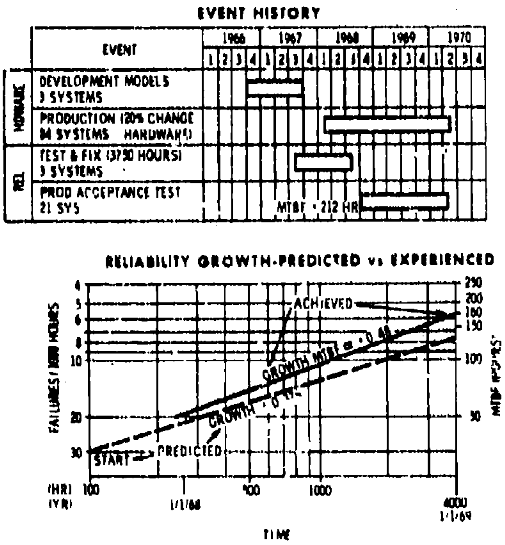


Figure 7. RPM Model - Program 3

Sample Application

In order to illustrate the decision-making power of the RPM model and to describe the steps in the methodology that a contractor will take, let us consider a sample application, typical of those confronting us in today's military environment.

A customer generates a requirement (Table II) and RFQ to design, develop, and deliver a new avionics equipment which violates no laws of physics, is expected to be within the state of the art, has a lead time of 36 months, and an apportioned MTBF from a higher level system require-

TABLE II. SAMPLE APPLICATION

RFQ REQUIREMENT
- NEW EQUIPMENT - WITHIN STATE OF ART
- R&D TARGET TIME - 36 MONTHS
- MTBF 150 HOURS - WEAPONS SYSTEM APPORTIONED
- R PROGRAM PER MIL-STD-785
- TEST PER MIL-STD-781 LEVEL F
- FACI AND CONFIGURATION CONTROL - 1st PRODUCTION ITEM

INITIAL CONTRACTOR PLAN
- COMPLEXITY
  - ESTIMATE - 11K, 220 HOUR PREDICTION
- HIGH RELIABILITY PROGRAM
  - DESIGN DISCIPLINES, R PARTS, SCREENING, EVALUATION TESTING
- TIME PHASE PLAN
  - 15 MONTH DESIGN, 6 MONTH MFG, 12 MONTH EVALUATION, 3 MONTH PRODUCTION TRANSITION
- IMPLEMENTATION OPTIONS
  - MINIMUM ASSETS
    - 1 EQUIPMENT, SPARES, 24 MONTH EVALUATION
  - COMPLIANT TIME
    - 2 EQUIPMENTS, SPARES, 12 MONTH EVALUATION
  - LEAST RISK
    - 3 EQUIPMENTS, SPARES, 8 MONTH EVALUATION
    - GROWTH CONTINGENCY 25%, 12 MONTH EVALUATION

ment of 150 hours. The reliability program is to be in accordance with MIL-STD-785 with testing per MIL-STD-781 test level F; First Article Configuration Inspection (FACI) and configuration control are required on the first production item.

Viewing these requirements, a contractor first determines a functional implementation plan and equipment schedule based on the technical exhibits, previous experience, equipment complexity, and program planning judgments. Let us assume the case of a responsible contractor who assesses the requirement as being within the state of the art and represents an equipment of 11K parts complexity. Using MIL-STD-217A as a departure point, a prediction of 220 hours is calculated, made possible by use of screened parts, applied under exacting application and derating criteria. This prediction meets the first RPM criteria by exceeding the minimum 125% of specified requirement.

The schedule milestones are established, based on past development experience, resulting in 15 months for design, 6 additional months for initial hardware manufacture and ambient test, 12 months for evaluation testing, and 3 months for final change documentation and incorporation prior to production FACI and configuration control constraints.

The second and third criteria of the model state that for a new design the initial hardware MTBF will be 10% of that predicted, and reliability growth will follow the Duane postulate. Employing these criteria, a reliability initial estimate and growth requirement based on the specifics of the selected implementation now can be structured. The initial capability for this new system is thus dimensioned as 22 hours, 10% of the predicted MTBF. A growth rate α of .5 is planned based upon a comprehensive reliability program executed through competent implementation of MIL-STD-785 and MIL-STD-781. The growth requirements, Figure 8, indicate that compliance can be achieved at 4800 hours of test time.

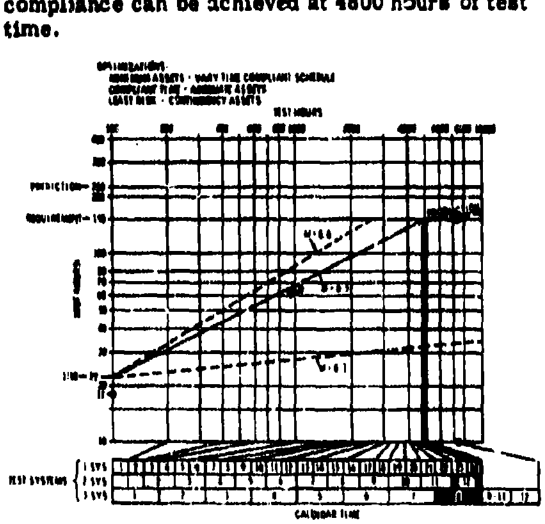


Figure 8. Planning Example

In implementation planning, optimization of the reliability program about individual program priorities is desirable and required. In this example, the contractor elects to consider optimization in three cases of program structuring: minimum assets, compliant time, and least risk. The objective is clearly to dimension and evaluate the alternatives and activity necessary to achieve required equipment reliability during development and prior to the production and user constraints. Based on a review of test experience with complex systems, it has been established for GE/AES products that 200 hours of test operate time can reasonably be achieved per system month of effort.

Operating within these bounds, let us now consider the test plan options open to the contractor to develop a compliant product. The first option, minimum assets, requires one system tested continuously for 24 months representing the least number of systems. The second option, a time compliant test, requires two systems tested continuously and concurrently for 12 months. The third option, least risk, requires three systems tested continuously and concurrently for 8 months, accommodating additional time for reaction to contingency including growth of up to 25% in product complexity. This growth reflects the case where an 11K part original estimate grows during detail implementation to a 14K part system.

From these optimizations, the magnitude of the program, kinds of disciplines, and available

tradeoffs bounding a successful program are now clear to management.

CONCLUSION

In conclusion, RPM is essentially a management tool for bridging the gap between stated reliability requirements and implementation planning. The RPM methodology, equally usable by buyer and contractor, is applicable to establishing plans, projecting effort, evaluating proposals and monitoring contract performance. Experience at GE/AES has shown that the RPM methodology in practice does address and effectively contribute to solving the reliability planning problem as dimensioned in this paper. This initial RPM presentation will hopefully foster amplification and refinement of the model to the point of a uniform industry accepted and practiced methodology.

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This report presents the results of a study to develop basic relationships capable of determining and predicting the reliability costs attributable to equipment reliability. The study is based on data derived during the development phase of equipment acquisition. The relationships, including incremental reliability gain related to incremental reliability cost, were developed using data from two manufacturers on ten equipments covering three reliability elements. The equipments cover a span of end use airborne and space environments.
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20. ABSTRACT (continued)

The reliability elements analyzed in the study are the reliability design program (includes prediction, failure mode and effect analysis, and design reviews); the reliability parts program (includes parts screening specification, parts standardization and control, and vendor control); and the reliability testing program (includes evaluation testing, equipment environmental screening, and reliability demonstration testing). To develop the relationships, two linear models were hypothesized. The first model relates resultant equipment reliability, the reliability costs and the equipment complexity. The second model relates incremental reliability gain to reliability element cost. The initial MTBF (equipment reliability prior to the start of a reliability program) is defined in terms of the normalized equipment complexity. Detailed discussions of data collection and analysis efforts along with step-by-step procedures for using the modeling results are presented in the report. Constraints and precautions to be applied in using the equational relationships are also included.